FINAL REPORT

Zinc Bromide Flow Battery Installation for Islanding and Backup Power

ESTCP Project EW-201242

SEPTEMBER 2016

Ryan Faries
Raytheon

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14. ABSTRACT

This Environmental Security Technology Certification Program (ESTCP) effort demonstrates the energy security and cost benefits of implementing a Zinc Bromide (Zn/Br) Flow Battery-based Energy Storage System (ESS) at the Marine Corps Air Station (MCAS) Miramar. The effort integrates an innovative Zn/Br Flow Battery and Intelligent Power and Energy Management (IPEM) technologies with the existing MCAS infrastructure, providing energy security and islanding capability, while reducing costs.

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1 INTRODUCTION

This Environmental Security Technology Certification Program (ESTCP) effort demonstrates the energy security and cost benefits of implementing a Zinc Bromide (Zn/Br) Flow Battery-based Energy Storage System (ESS) at the Marine Corps Air Station (MCAS) Miramar. The effort integrates an innovative Zn/Br Flow Battery and Intelligent Power and Energy Management (IPEM) technologies with the existing MCAS infrastructure, providing energy security and islanding capability, while reducing costs.

Improving energy security and reducing consumption are key strategic objectives of the Department of Defense (DoD). Achievement of these objectives is limited by commercial power grid vulnerabilities and intermittencies of available renewable resources. Low cost, large scale energy storage systems are needed to address these limitations.. Energy storage is a preferred approach to enable off-grid 'islanding', improving energy security through grid-independent operation. The ESS provides a reliable source of energy in the event of a cyber or physical attack, natural disaster or technical malfunction.

This project started in the middle of 2012 and concluded demonstrations at the end of 2015. Modifications to existing Miramar infrastructure were required to accommodate the ESS and allow for islanded operations. The system design phase occurred from 2012 to 2014 and went through changes in the supplier of the ZnBr Flow Battery. The pre-construction phase for the program started in the fall of 2014 and the construction started in the spring of 2015. The new utility switchgear and ESS were installed and commissioned at the end summer of 2015. The demonstration phase of the project started in the Fall of 2015 and concluded at the end of 2015.

This project was intended to demonstrate that an energy storage system can be used as a replacement for conventional diesel generators for emergency back-up power and demonstrate that an ESS can function with renewable energy systems within a microgrid islanded operation to enhance energy security. This project also intended to show that an ESS can be used for economical benefits by changing the load profile of a building by charging and discharging the battery according to a controlled schedule.

1.1 BACKGROUND

The Marine Corps Air Station, located at Miramar, CA has completed a significant study for locating and sizing Renewable Energy (RE) generation in order to demonstrate progress towards reaching Net Zero operation; e.g. a Military installation that produces as much energy on or near the installation, as it consumes in its buildings and facilities. During the initial study, Energy Storage Systems were briefly discussed, but not actively pursued due to constraints of previous programs. MCAS Miramar has identified a need to manage the variable power generation of the installed RE systems without adding additional sources. To improve a base's overall energy security, an ESS can bridge power gaps in the RE generation either by load shifting, peak shaving, or arbitrage.

1.2 OBJECTIVE OF THE DEMONSTRATION

There were two main objectives of this project. The first objective is to demonstrate that Energy Storage enables the use of existing renewable energy systems that normally are unavailable during

a grid outage, to ‘Island’ a building circuit for 72hrs without a diesel generator. The genesis of this objective lies with the current large deployments of renewable PV systems that have been installed by the DoD. The majority of these PV systems were installed to meet renewable energy goals without considering their interaction with microgrid and islanding energy security scenarios. This means the systems have built in safety features such as UL1741 that shut the systems down in the event of a grid outage. This project intends to demonstrate that an ESS can provide voltage control capability in islanded operations that allow the functionality of existing PV systems in microgrid mode at high penetration levels. This will enhance the energy security of the base in the case of an extreme event (e.g. cyber attack, utility maintenance, or natural disaster), demonstrate Energy Storage microgrids provide increased capability of existing PV installations.

The second objective is to demonstrate that an Energy Storage System can peak shave for demand charge avoidance. Many DoD facilities have been attempting to reduce their operational energy costs by implementing a variety of energy efficiency and renewable energy programs. One of the biggest costs to many facilities is not in the cost of energy purchases but in the demand charge issued to the facility based on its load profile. This project was designed to allow the ESS to be programmed to charge/discharge according a defined peak shaving schedule. This is to show that Zn/Br system can charge during off peak hours and discharge during peak hours reducing peak load by the power output of the battery. The intent of this objective is to show that Energy Storage can provide economic benefit in addition to improved energy security.

The field demonstration for this project was intended create operational scenarios for which the two main objectives could be demonstrated. To demonstrate the energy security improvement the project set up a scenario where power was interrupted to the microgrid circuit and the system would provide back up power for the outage meeting the load requirements of the microgrid. To demonstrate the peak shaving capabilities the project set the microgrid system up so that the ESS could charge and discharge on a user created schedule and data could be collected on the systems capability to peak shave during defined hours.

1.3 REGULATORY DRIVERS

The National Defense Authorization Acts 2010-2012 and Energy Independence and Security Act of 2007 have shaped the Navy’s microgrid strategy. This has created five major energy goals issued by the secretary of the Navy and shared in similar sense with the other branches of the military. The five energy goals are listed in Figure 1-1 below.

Reduce Energy Consumption & Intensity	• By 2020, USN will reduce energy consumption and intensity by 50% from a 2003 baseline.
Power from Renewable Sources	• By 2020, 50% of total ashore energy will come from renewable sources.
Net-zero installations	• By 2020, 50% of installations will be net-zero consumers.
Reduce Non-Tactical Petroleum Use	• By 2015, reduce petroleum used in commercial vehicle fleet by 50% from a 2009 baseline.
Increase Energy Security	• Provide reliable, resiliant and redundant power to increase the energy security of mission critical assets.

Figure 1-1: Energy goals from the Secretary of the Navy.

The goal for increased energy security is one of the main drivers for this project. It is common for our country's military bases to get their power from their local utility companies. Utility companies and their power distribution networks can be vulnerable to events such as extreme weather or even cyber attacks. The San Diego area was subject to an 11 hour blackout back in 2011 due to an error during routine maintenance of the distribution system (Figure 1-2). This creates the need for back-up generation systems and the current status-quo is to use diesel generators. In the spirit of trying to meet the Navy energy goals the Navy is looking at ways to leverage their renewable investments to replace diesel burning systems. The Navy is also looking for creative ways that it can use microgrids and energy storage to improve its load profile to avoid high peak charges and participate in economic incentive programs such as demand response.

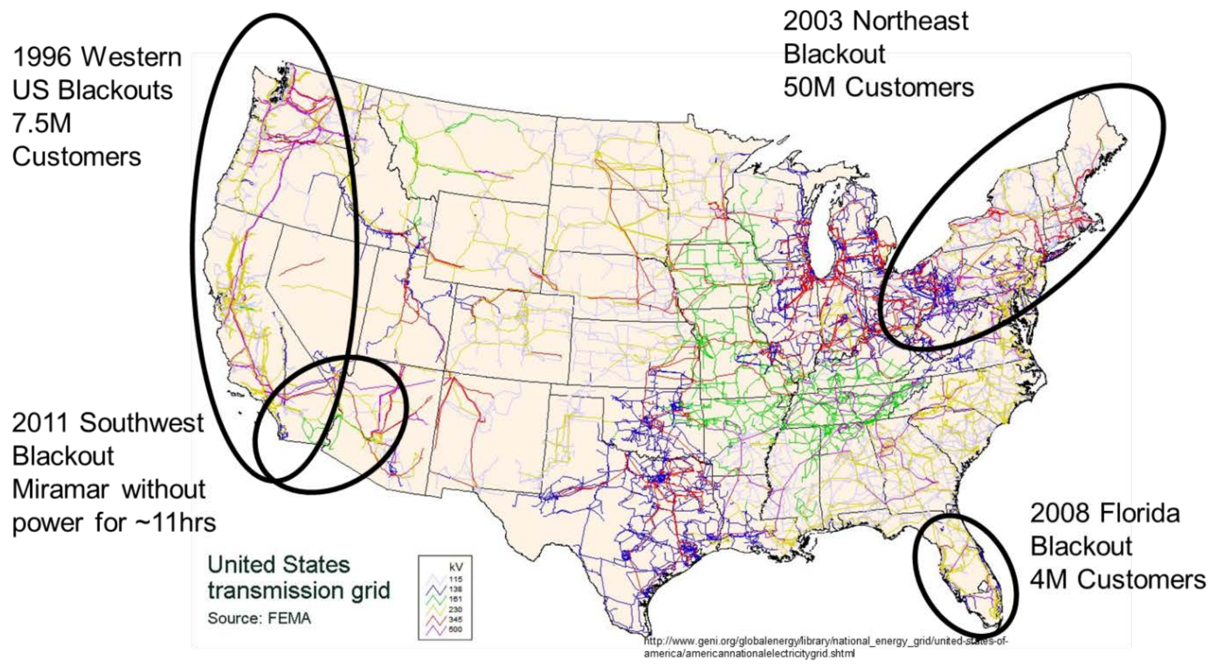


Figure 1-2: Image of the US electrical distribution system taken from the FEMA website.

Energy storage can play a key role in meeting the energy goal and mission needs of our military installations. The existing electrical distribution system was built around the production/use principle that electricity must be produced when it is needed and consumed once it is produced. This principle works when a generation network is in place that is monitored and controlled predictably. The ability to control the generation has become more difficult with the increase of renewable energy systems such as solar photovoltaics (PV) and wind. Both PV and wind systems generate power based on unpredictable cycles of nature. At very low levels of renewable energy penetration this can be handled through the existing generator network to keep the grid balanced. The ability to store excess energy acts as a key enabler to increasing levels of RE penetration.

2 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Technology Description

The Zn/Br flow battery technology manufactured by Primus Power was chosen to be the storage provider over other storage technologies for several reasons described below. The key determining factors for islanding and renewables integration applications for Miramar are: low cost, energy storage capacity, intelligent system control, transportability, cycle life, system lifetime, and safety.

The traditional Zn/Br batteries contain a solution of zinc bromide in two tanks. During charge of the battery, zinc is electroplated on the anode and bromine is sequestered in a polybromide complex that is stored in the electrolyte storage tank. On discharge, the polybromide complex is returned to the battery stacks, and zinc is oxidized back into the electrolyte solution, forming the identical Zn/Br solution the unit started with (Figure 2-1). This type of battery leverages many years spent developing proper plating systems in a novel storage approach.

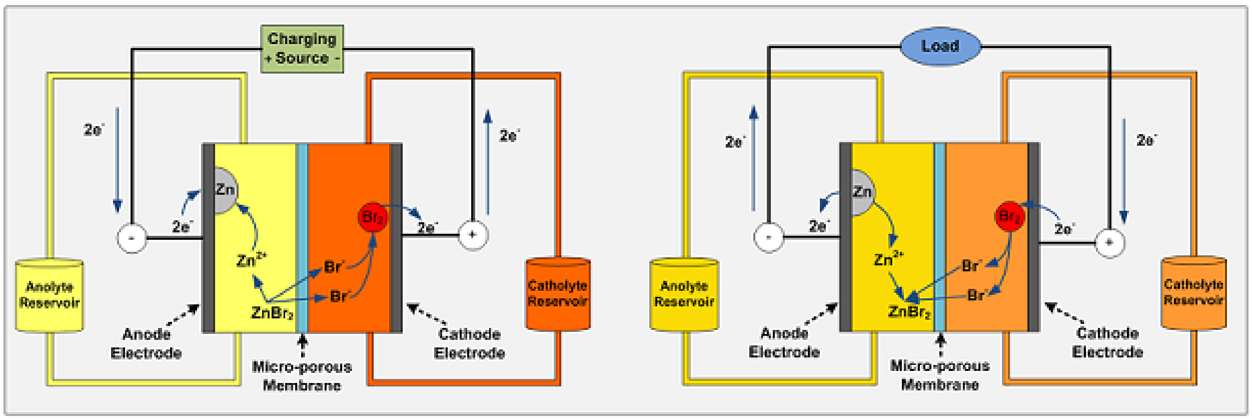


Figure 2-1: Schematic of a traditional Zn/Br cell with two electrolyte flow loops.

The traditional Zn/Br cell design uses carbon coated felt paper as the electrode surface. The cells also have two separate electrolyte tanks for capturing the anolyte and catholyte separately during charge and discharge. These separator membranes and carbon paper often are subject to degradation and contamination and are a common failure mechanism amongst Zn/Br batteries that requires reoccurring replacement. Traditional Zn/Br needs to be replaced after 1500 cycles which would constitute replacement every 4.1 years if cycled daily.

Primus Power took a different approach to their Zn/Br cells. Instead of using carbon coated felt paper for their electrodes Primus utilizes an activated solid titanium electrode for its Zn plating surfaces. Using a titanium electrode provides Primus the capability to use a single flow loop of electrolyte as opposed to dual flow loops as well as eliminate the need for an ion exchange membrane, which is an early failure mechanism in tradition Zn/Br cells. This reduces the number of tanks required and pumps for managing the electrolyte (Figure 2-2). The titanium electrodes also provide better energy density when compared to traditional Zn/Br 3.1 kWh/ft^2 vs1.7 kWh/ft^2.

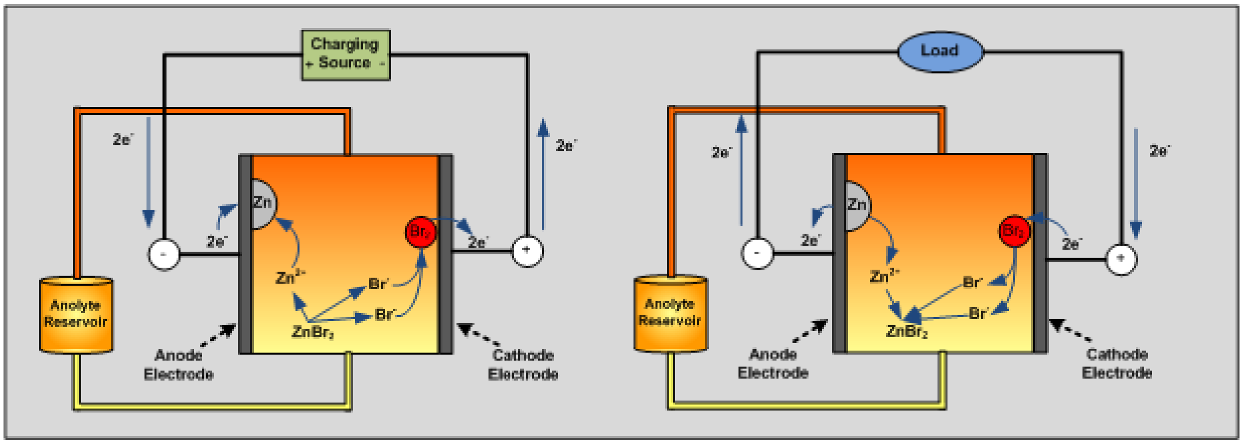


Figure 2-2: Schematic of Primus' approach to a Zn/Br cell using a solide titanium electrode and a single flow loop of electrolyte.

Primus' ESS has three main subsystems that encompass the entire energy storage system. The ESS has an EnergyPod which contains the ZnBr EnegyCells. The EnergyPod is connected to a PowerBox that contains the power electronics of the ESS as well as the Battery Management System. The system also has a chiller used to provide cooling to the ESS. The ESS was specified at the onset of this program to be 250kW nominal power and 1MWh of energy capacity at a C/4 discharge rate. Primus uses a 30kW building block called an EnergyCell to build their EnergyPod system. During initial tests of the EnergyCells it was determined by Primus that 14 EnergyCells would be required to achieve the project goals for islanding and peak shaving. The EnergyPod system was designed to be packaged in a 20ft container coupled with the PowerBox that was housed in a 20ft ISO container. An early rendering of the system is shown in Figure 2-3, the EnergyPod was then expanded into a 40ft container and the updated rendering is shown Figure 2-4, an image of how the system was intended to look during construction planning is shown in Figure 2-5, and a photo of the complete system installed is shown in Figure 2-6.

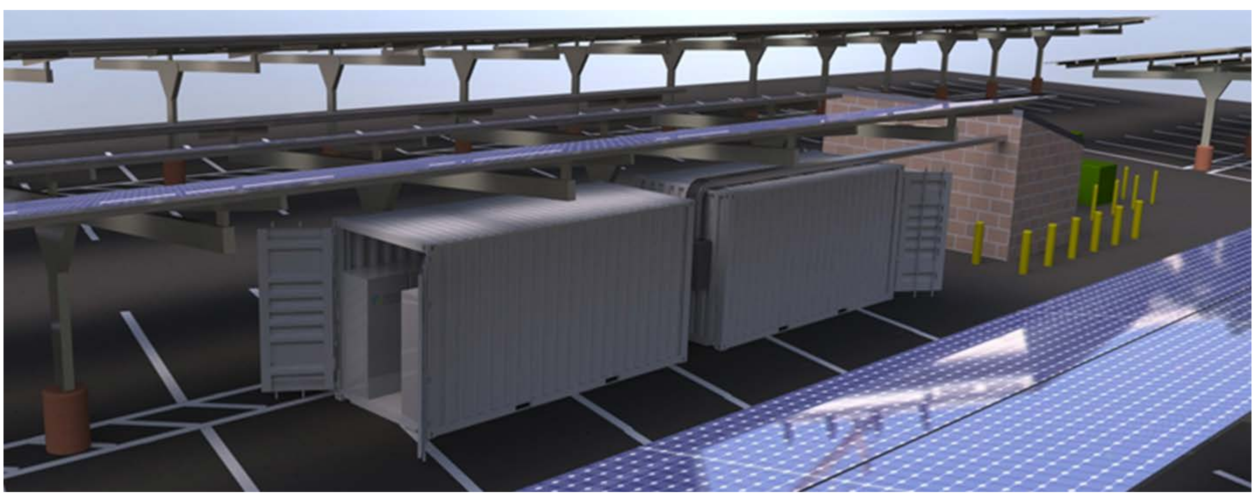


Figure 2-3: Early rendering of ESS located at MCAS Miramar.

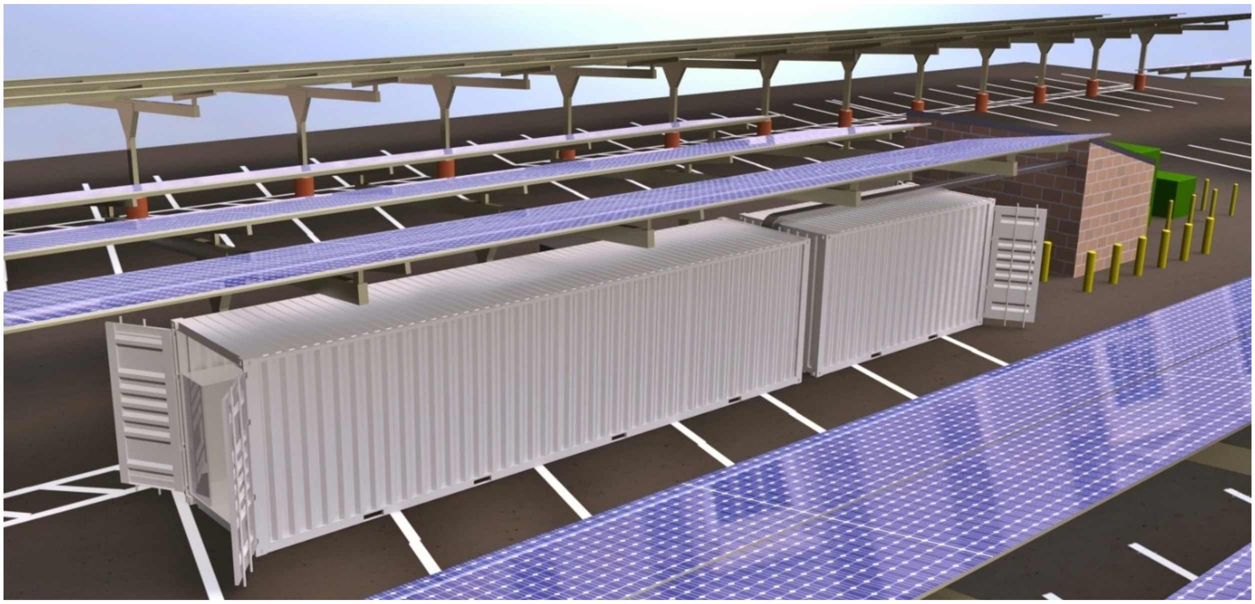


Figure 2-4: Illustration of Primus EnergyPod system complete with Zn/Br cells, power electronics, and thermal management.

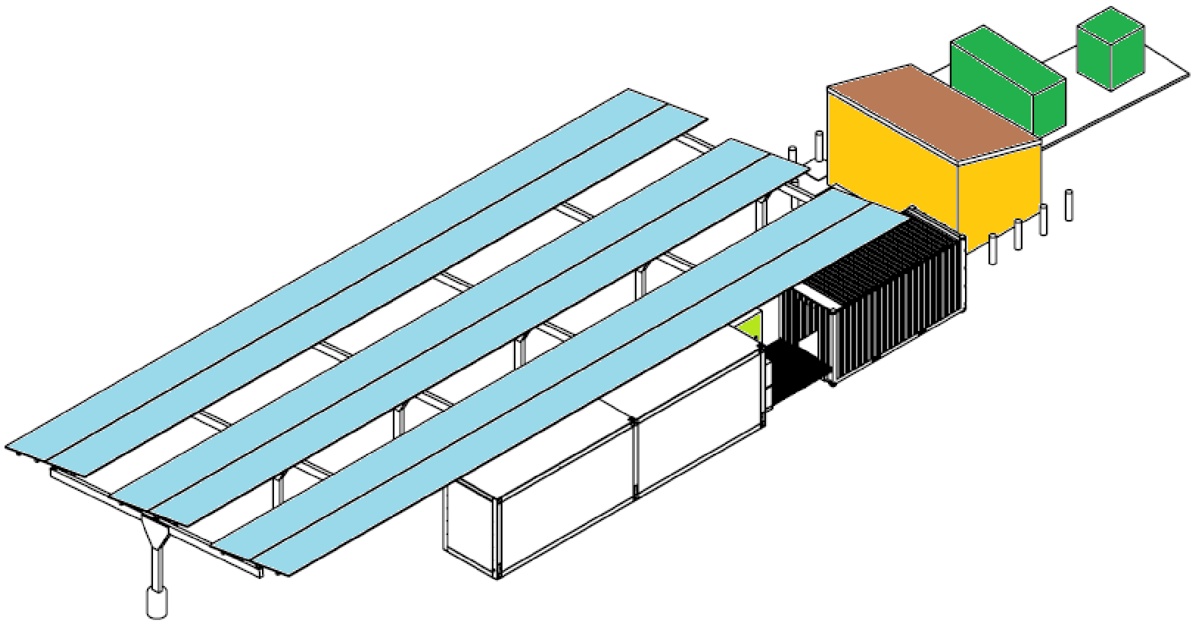


Figure 2-5: Isometric view of the construction plans.

Figure 2-6: Photo of installed system at MCAS Miramar.

2.2 TECHNOLOGY DEVELOPMENT

The developmental timeline for Primus' Zn/Br technology is summarized in Figure 2-7 below. Primus' early development started in 2009. When Primus was put under contract in late 2012 for this project they were operating at TRL4 and progressively matured their technology to TRL5 at

the conclusion of the 3rd party testing of their 30kW EnergyCell unit completed in the fall of 2013 by Sandia National Laboratory (SNL), then to TRL6 at the conclusion of this demonstration. The following section will describe the TRL advancement of Primus' technology leading up to the demonstration.

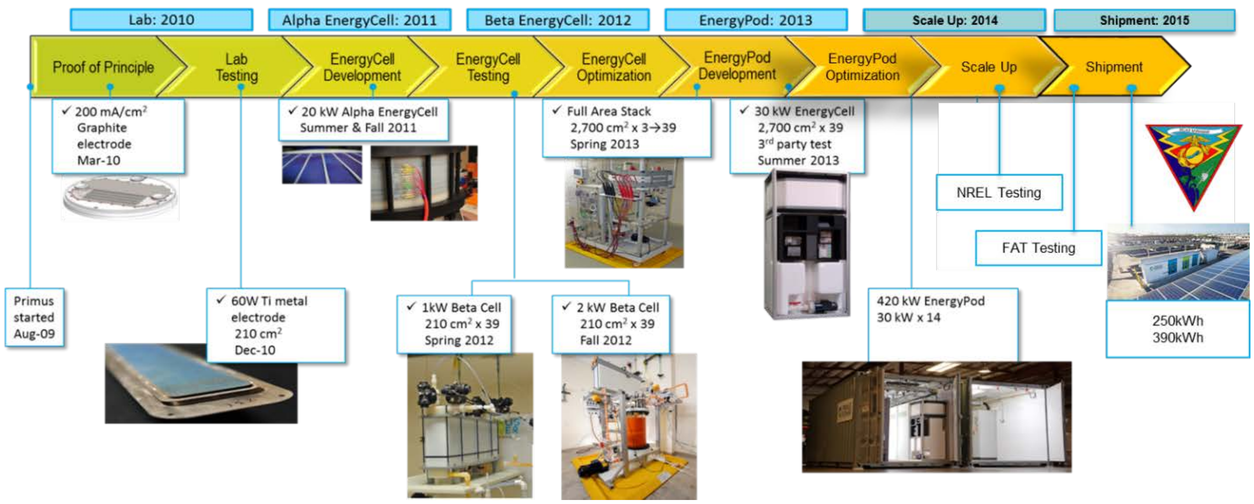


Figure 2-7: Developmental timeline for Primus EnergyPod system.

At the beginning of 2013 Primus Power was in process of building the first EnergyCell building block for their energy storage technology. They had already successfully built and tested a variety of smaller cells that validated the technology at 1-2kW scale. In summer of 2013 the first 20kW EnergyCell was finished being built and was ready for characterization testing. Primus chose to have the EnergyCell 3rd party tested by Sandia. The test setup from the Sandia testing is shown in Figure 2-8 below. Sandia performed a variety of performance tests on Primus' EnergyCell.

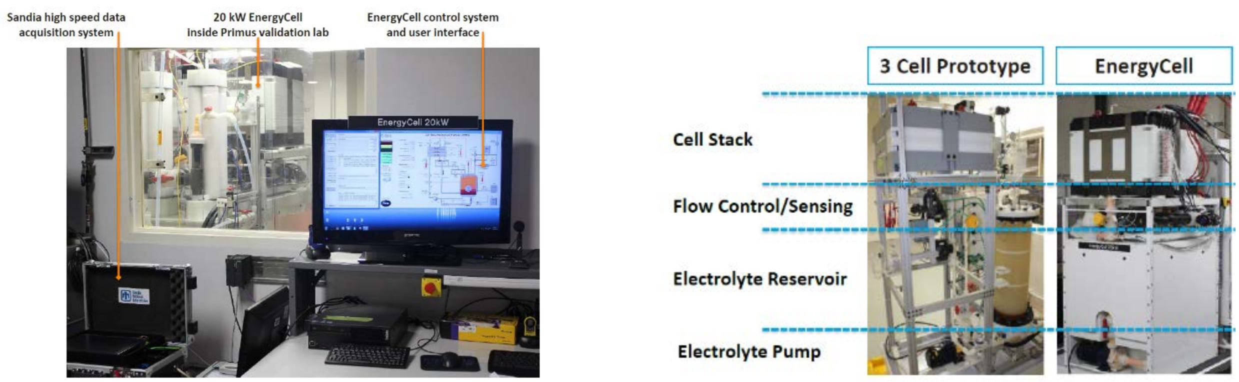


Figure 2-8: Photo of Sandia National Laboratory 3rd party testing of Primus Powers EngergyCell at Hayward CA.

The goals for the Sandia testing were to:

- Measure ability of EnergyCell to perform discharge at various durations
- Measure round trip efficiency of charge-discharge cycles
- Measure power rating of the EnergyCell
- Measure EnergyCell step response to command charge/discharge

The Sandia 3rd party testing results are summarized in and were briefed to the ESTCP office in November of 2013. The testing validated that Primus' technology provides the power, efficiency and responsiveness needed for the demonstration. A couple of the takeaways from the Sandia tester were:

- Power exceeds 20kW requirement (30+kW capable)
- Transient response consistent with demonstration application requirements
- Energy efficiency is consistent with expectations

The testing also showed additional work was required to meet demonstration islanding duration objectives with reasonable load shedding. At 20kW EnergyCell was discharged at 20kW and achieved an energy capacity of 25kWh at just over 1 hour of discharge time. At 3kW of discharge power the capacity test resulted in 2+hr (43kWh) performance. In order to meet our system level performance objective with the number of EnergyCells originally proposed each energy cell would need to have an EnergyCapacity of 80kWh at 20kW. After the testing Primus showed that in-house testing of smaller cells had exceeded 40kWh with altered additives and discharge controls. Primus planned to continue developing electrolyte chemistry and charging modifications to meet the 80kWh objective in their SOW.

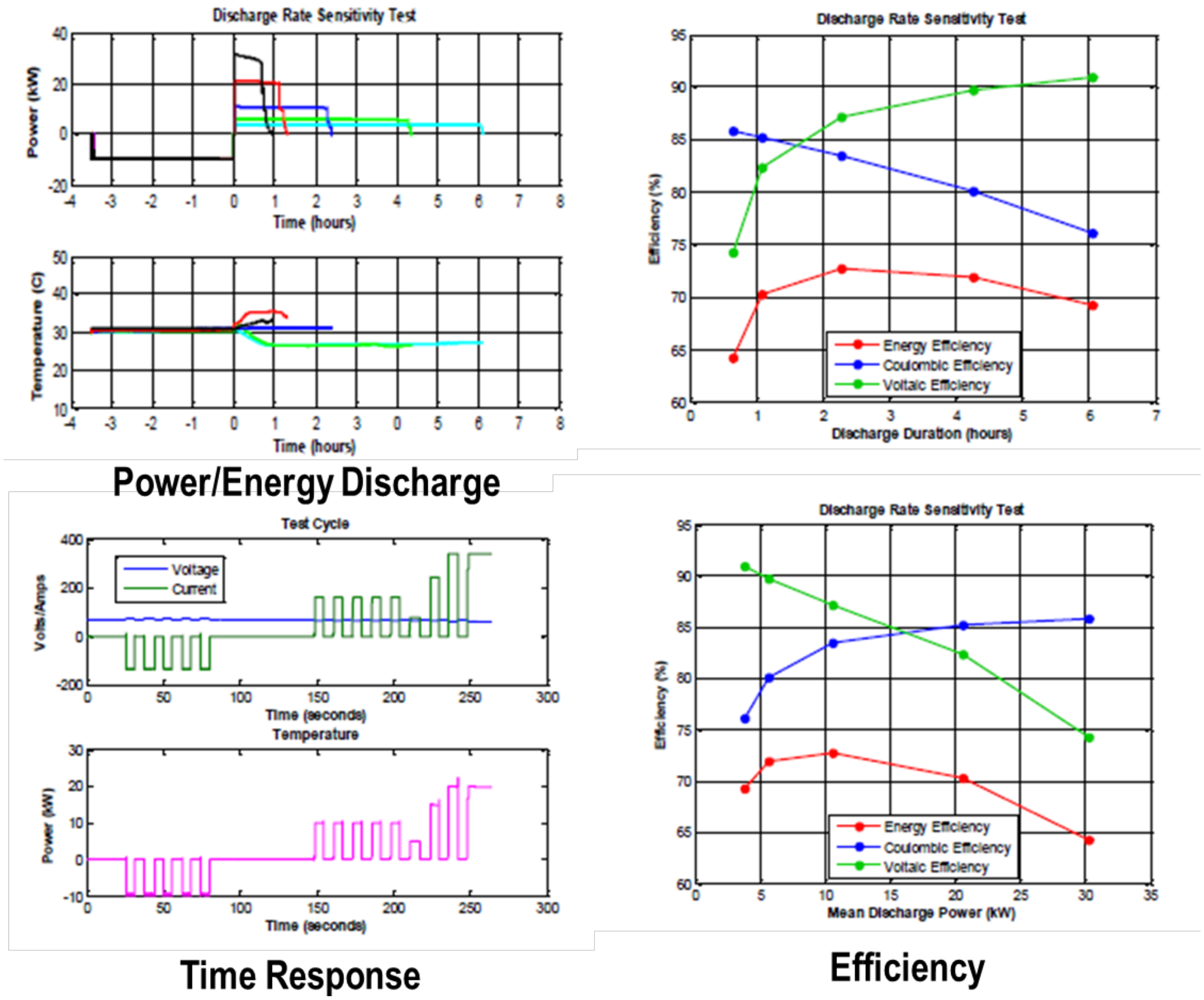


Figure 2-9: Summary of results of Sandia 3rd party testing.

The results of the Sandia testing provided needed insight into the development and scale up capability of Primus Powers first generation ESS. The EnergyCells performed very well in terms of power density and responsiveness to meet the load following capabilities required for the microgrid however the energy density performance was not meeting initial expectations at larger scales. The original EnergyPod was envisioned to be in a 20ft ISO container with the 14 EnergyCells, however based on the energy density and capacity results from the Sandia testing the size of the EnergyPod would need to expand to a 40ft container and further development would be needed to improve the energy capacity to achieve the 750kWh threshold requirement. Primus power committed to continue working on increasing their energy density and energy capacity of its EnergyCells but needed more time to make improvements. Two options were discussed at the November briefing with the ESTCP office.

<u>Option #1</u>: Deliver 250kW/500+kWh System in 40' + 20' ISO in August 2014

- Pros: Hold to original schedule
- Cons: Requires excessive load shedding to meet 72hr islanding objective, no opportunity to improve performance/packaging density over current system, delivered system will feature unique technology not common with other Gen1 system deliveries
- Risk Level: Confined to BoP. System will employ the same design as the SNL- tested EnergyCell and 3-cell prototype

<u>Option #2</u>: Deliver 250kW/1000kWh System in 20-40' + 20' ISO in January 2015

- Pros: Meets original ESS performance specs to support 72hr islanding objective with reasonable load shed, may meet original size/volume specs delivered system common with other Gen1 deliveries
- Cons: Requires 6mo extension
- Risk Level: Mitigated through flexibility on deliverable form factor. If further electrolyte development does not yield required performance improvements, Primus will deliver required (250kW/1000kWh) capacity with existing technology

Raytheon and MCAS Miramar recommended Option #2 to the ESTCP office, based upon Primus Power commitment to performance specifications and MCAS Miramar priorities. The ESTCP office agreed with the assessment and the projected delivery of the battery was re-forecasted to early 2015 with periodic assessments of system performance.

While Primus was working on scaling up and building their large scale system in 2014, Raytheon orchestrated hardware in the loop testing of the Miramar microgrid utilizing the National Renewable Energy Laboratory (NRELs) Energy System Integration Facility (ESIF) funded by Raytheon outside the funding of this ESTCP program but provided was directly beneficial to this project. The intention of the testing was to provide high-fidelity evaluation of the MCAS Miramar microgrid in a simulated operational environment with real hardware in the loop testing with full-scale/full power simulated sources and loads. The system testing reduced a lot of risk on integrating the IPEM controller to manage the existing Advanced Energy PV inverters at MCAS Miramar, the Primus ESS, and the various metering and control logic of the microgrid. The testing at NREL was designed to re-create the designed Miramar microgrid at as high a fidelity as possible. Figure 2-10 below shows a one line diagram for the Miramar microgrid circuit for the ESTCP project.

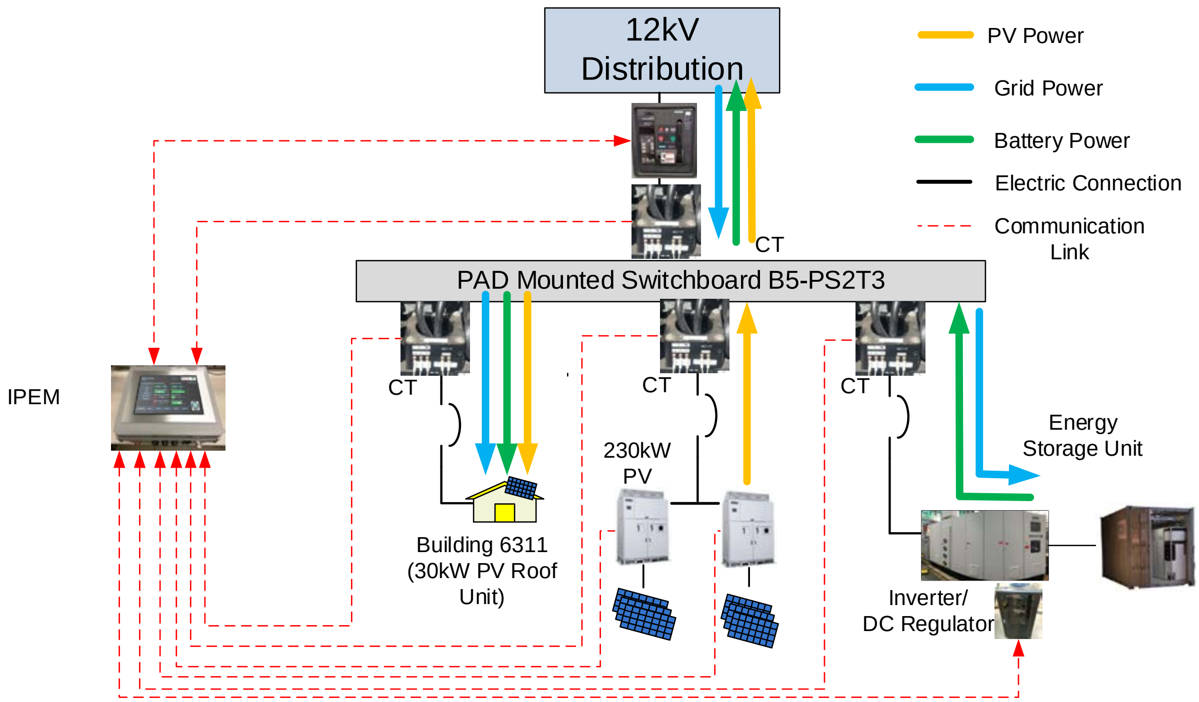


Figure 2-10: One line diagram for the MCAS Miramar microgrid circuit for the ESTCP project.

Figure 2-11 shows the one line diagram for the circuit that was designed to be used at NRELs ESIF facility. The NREL system utilized the same PV inverters that exist at MCAS Miramar, a similar main breaker point of common coupling, and the same inverter & BMS utilized by Primus' ESS.

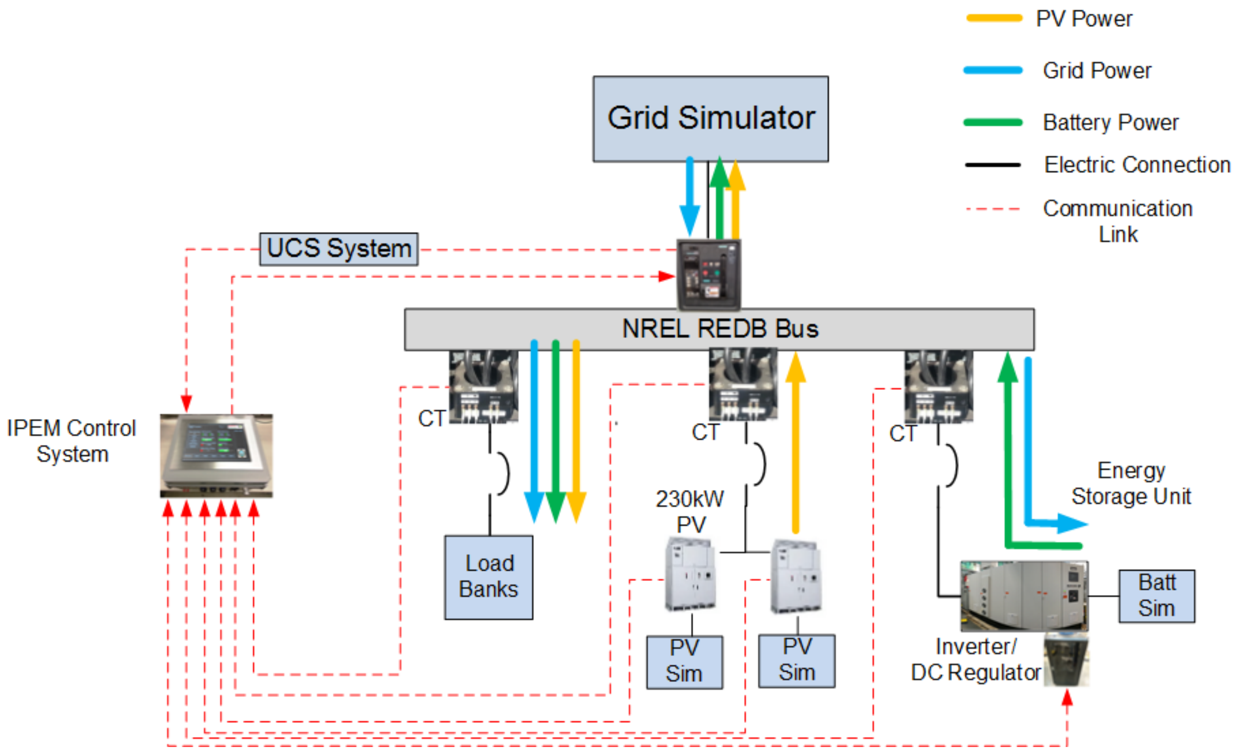


Figure 2-11: One line diagram design for test setup at NRELs ESIF facility.

The end result for the configuration used at NREL is shown in the detailed single line diagram shown Figure 2-12 below.

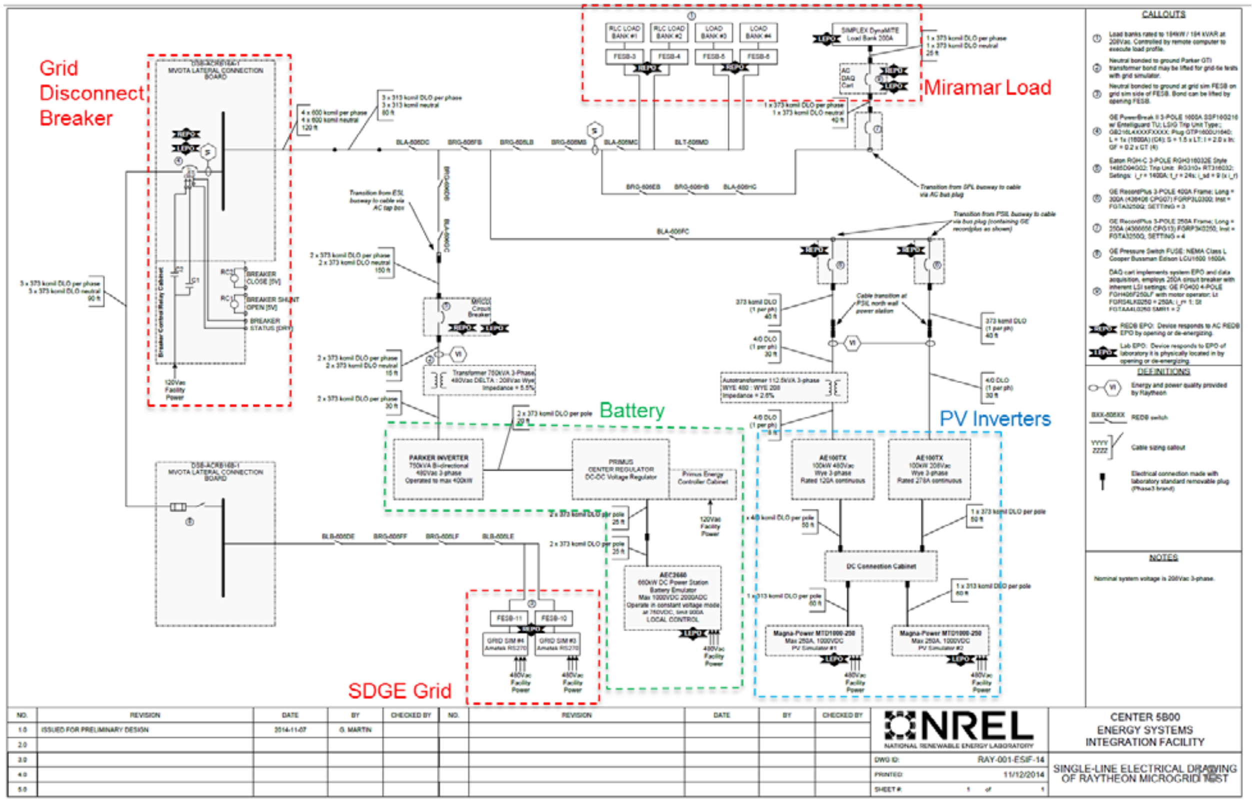


Figure 2-12: Detailed single line diagram implemented at NREL for ESIF testing.

During the course of testing Raytheon hosted a demonstration of the system with MCAS Miramar stakeholders and a representative from the US Marine Corps Headquarters (Randy Monohan). Randy was the MCAS Miramar station energy manager when this project was originally proposed and one of the earliest advocates in the project.

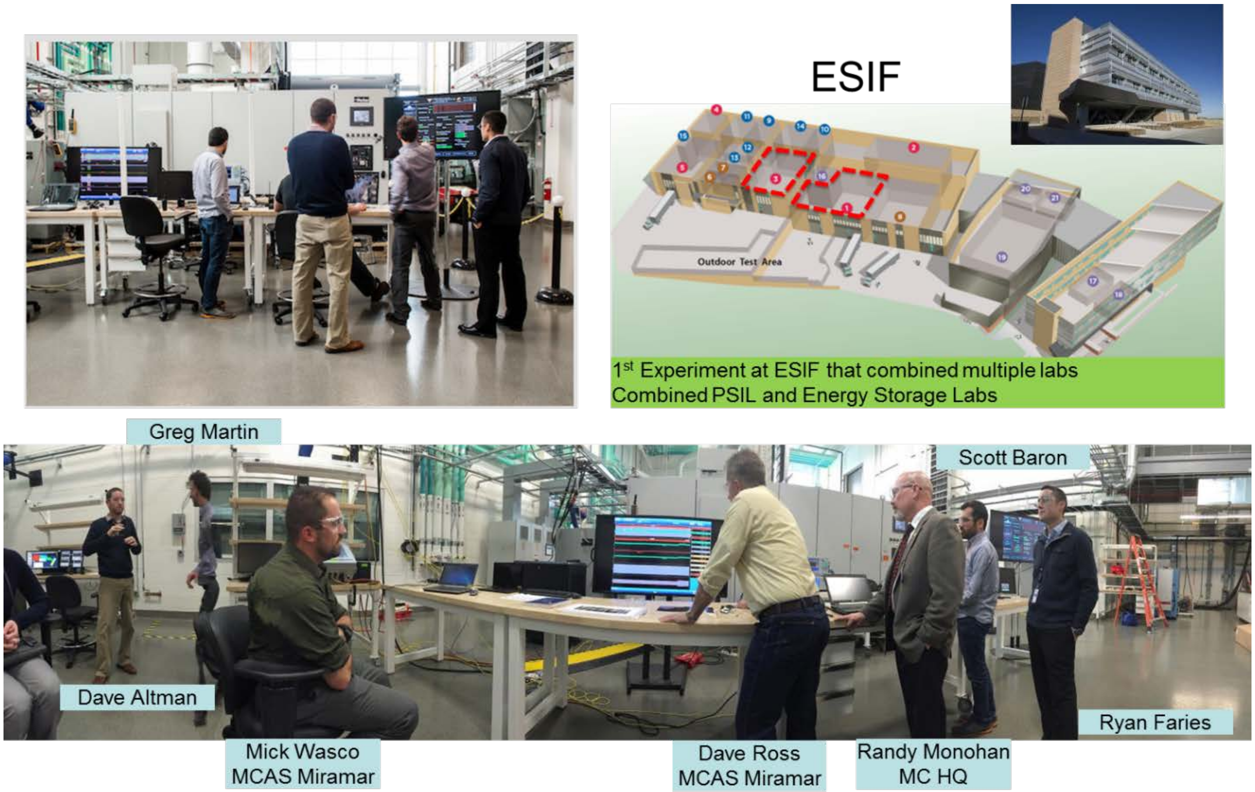


Figure 2-13: Photos showing the live testing at NRELs ESIF facility with MCAS Miramar and USMC personnel.

Figure 2-14: Photos of the various equipment that is part of the NREL testing. The top left image is of Primus Powers 760kVA Parker grid tied inverter that is the main element in Primus' power electronics subsystem. The bottom left is of a 480 to 208 transformer, the bottom second from the left is Primus' EnergyBlock controller which manages Primus AC & DC busses. The bottom third from the left shows the capacitor bank within the Parker inverter. The right most image shows the AC breaker for the Parker inverter and the local HMI display.

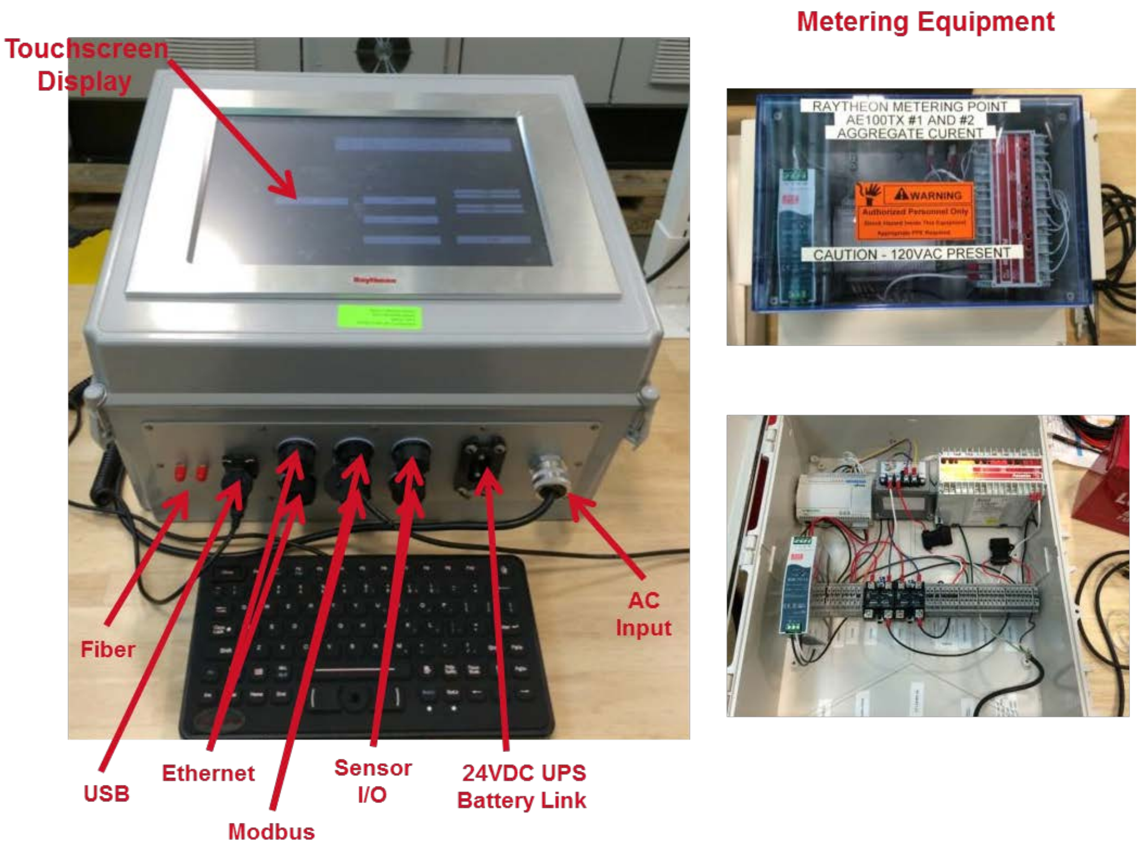


Figure 2-15: Photos of the IPEM controller and ancillary equipment used during the NREL testing.

The results of the NREL testing are summarized below:

Table 2-1: Summary of results from NREL testing.

Goal	Result
The black start sequence and transition to islanding work as anticipated within the 1hr time requirement	Demonstrated automated back start sequencing
The ESS inverter and PV inverters power share properly in islanding mode	Verified load sharing across operating range (0-200kW, 0.1-1.0PF)
The UL1741 anti-islanding algorithms do not destabilize the ESS inverter in voltage control mode	No issues observed
The PV penetration be pushed to >50% without de-stabilizing the ESS inverter in voltage control mode	Successfully run up to 100% PV penetration (w/bi-directional power flow to ESS)
The system does not destabilize due to dynamic PV curtailment and the system can handle load step requirements for Miramar's load	Characterized PV curtailment response timelines in response to increasing and decreasing load changes
The system meets IEEE1547.4 requirements for power quality.	No issues staying within trip points

After the completion of the NREL testing at the end of 2014 Primus was finishing building up its full scale system. Primus was ready to perform its Factory Acceptance Testing (FAT) of the completed ESS at their Hayward facility in May of 2015. The purpose of the FAT was to assess the performance and functionality of the system compared to performance objectives defined in their statement of work.

During the course of the build of the ESS Primus Power was continuously trying to improve its energy capacity capabilities of their EnergyCells based on the original assessment by the Sandia testing. At the time of the FAT Primus presented their current state of the energy capacity available with the configuration of EnergyCells that were to be delivered to MCAS Miramar. Figure 2-16 below shows the progression of meeting the targeted energy capacity as Primus was able to manufacture more of its EnergyCells to populate the system.

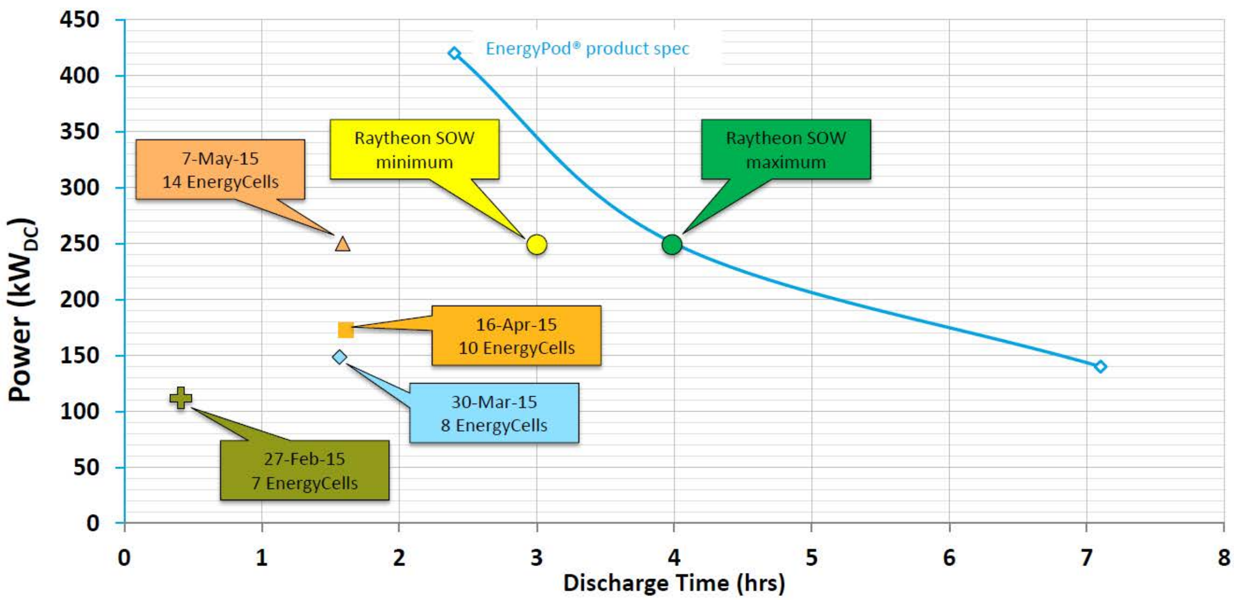


Figure 2-16: Energy capacity timeline and scale up from Primus Power since the November 2013 briefing.

The FAT testing included the following test objectives and the results are summarized below

FAT Test 1: Peak Shaving

The objective of the Peak Shaving test was to demonstrate that EnergyPod is capable of storing energy during off peak hours and push 250kW back to the grid during peak hours. The summary of test results are shown in Figure 2-17 below and show that the ESS is capable of charging and discharging at 250kW. It is important to note that the power output of battery is the net output power of the entire Energy Storage System. This means the battery output power minus the auxiliary power to the battery which includes: the control power to all the pumps, power electronics, inverter, chiller and the heaters. It is important to mention this as various energy storage systems have a separate auxiliary power requirements in their systems and don't subtract it from their output power when providing ratings.

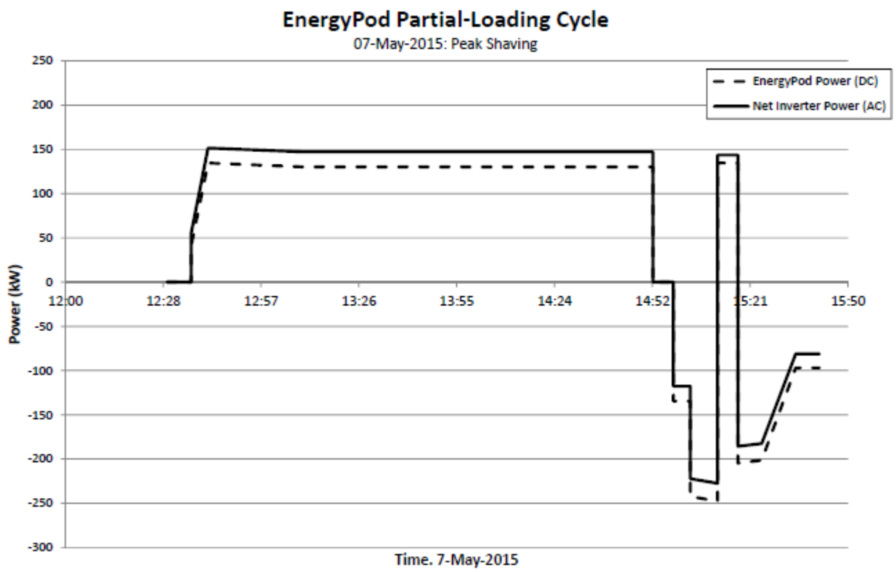


Figure 2-17: Results of the Peak Shaving Test during the FAT. Note the peak charge power is 140kW and the peak discharge power is 225kW.

FAT Test 2: Energy Storage Capacity

The objective for the Energy Storage Capacity test was to demonstrate the Energy storage capacity capability in grid tie mode. The summary of test results are shown in Figure 2-18 and Figure 2-19 below. The energy capacity capability of the ESS was determine to be 390kWh during the FAT. Figure 2-19 shows the anticipated relationship between discharge power and DC-DC energy capacity. The curve shows the most optimal efficiency for the system is when the EnergyCells are discharged at 10kW (140kW at scale with 14 EnergyCells).

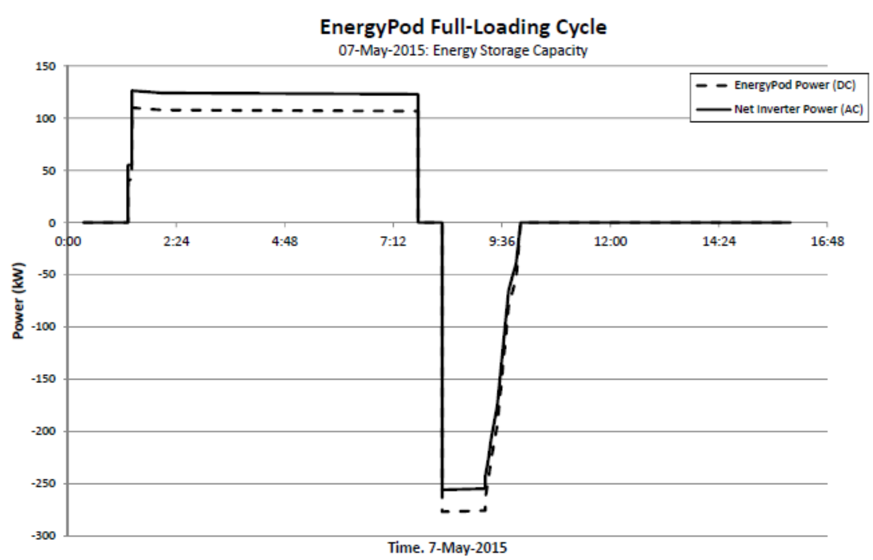
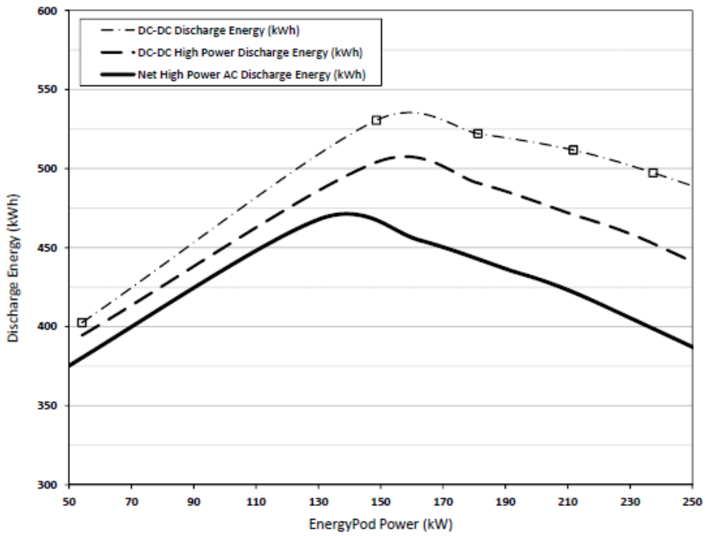


Figure 2-18: Results of the Energy Capacity testing during the FAT. Note the total charge duration is 6hrs and 20 min. The peak discharge power is 250kW and the total discharge energy recorded is 390kWh.



Discharge Data	
DC-DC Discharge Power (kW)	DC-DC Discharge Energy (kWh)
54.2	402.6
148.6	530.5
181.2	522.1
211.8	511.7
237.4	497.3
425.2	372.0

NOTES

1. All data assumes 770 kWh charge loading on EnergyPod
2. Data for highest and lowest DC-DC Discharge Power (425.2 kW / 54.2 kW) extrapolated EnergyPod running fewer than 14 EnergyCells
3. High Power Discharge Energy (kWh) calculated as fraction of energy discharged above 95% of EnergyPod Power set-point
4. Net High Power AC Discharge Energy (kWh) assumes
   - 1 kW / EnergyCell auxiliary power consumption
   - Inverter efficiency loss of 3% of EnergyPod DC power

Figure 2-19: Energy Capacity as a function of Discharge Rate shown on the DC output of the ESS.

During the course of investigating the energy capacity limitation of the EnergyCells it was determined that the configuration of the flow channel frames within each of the EnergyCells was causing non-uniform zinc plating across the plating area of the electrodes. The non-uniform plating was leading to Zn inlet edge ridges that cause early shortening as the zinc reaches the top of the opposing electrode earlier than the other areas of the electrode. Primus presented solutions that provided better electrolyte flow across the electrode reducing the non-uniformity allow more zing to be plated across the electrode surfaces improving the energy capacity. The new design of the cell frames were still in their test phase and would require retrofits of all 14 EnergyCells that were ready to be deployed further delaying the program.

FAT Test 3: Islanding capability (Black start)

The objective of the Islanding Capability test is to demonstrate that in islanding mode the Central Regulator (CR) can regulate the bus voltage while the inverter creates the grid to supply power to any load connected to the island. This test has two important aspects. The system needs to be able to start the EnergyCells and boost the bus voltage in order to enable the inverter to create the island by putting out 480vac 3ph output.

Test Procedure:

1. Open the main disconnect switch to the Grid and lock out tag out the disconnect switch
2. From the EnergyBlock GUI select Islanding operation
3. The system shall:
4. Turn the Aux. power to the EnergyPod and inverter
5. Send the EnergyCells into the discharge mode
6. Charge the bus voltage to 750vdc
7. Start the inverter

Summary of test results are shown in Figure 2-20 below.

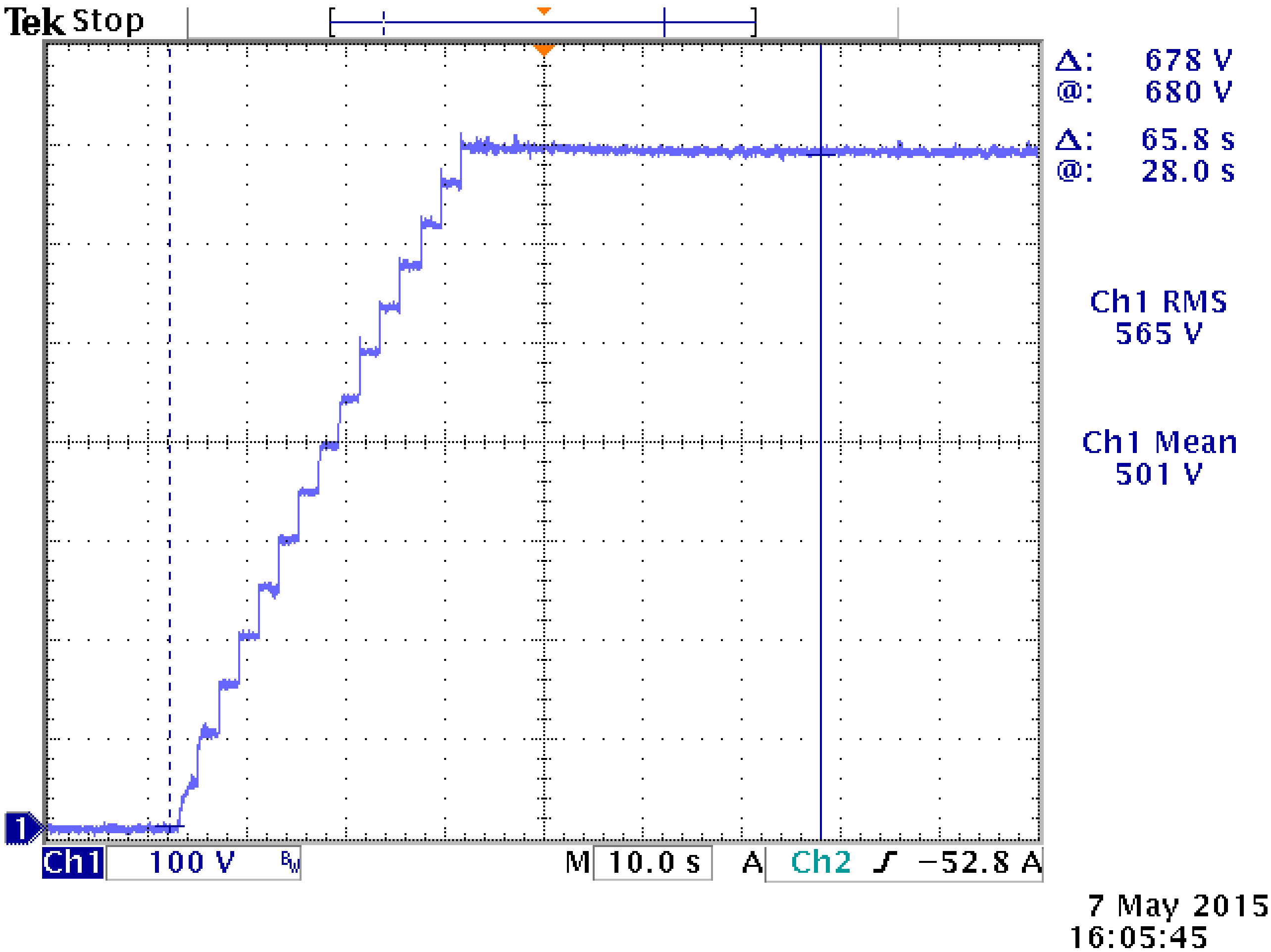


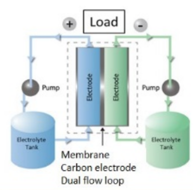
Figure 2-20: Oscilloscope screenshot showing the connected logics of the EnergyPod and PowerBox. The inverter was started in islanding mode. The image shows the bus voltage being regulated continuously.

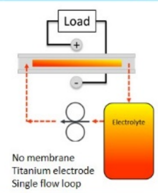
At the conclusion of the FAT testing the ESS was demonstrated to be functionally operational however still lacking in the desired Energy Capacity performance requirements defined in the SOW. At this point in the demonstration Primus Power's team had made tremendous amount of progress and investment to get the system to function as required. As the program did not have enough time or resources to continue developing the ability to increase the energy capacity any further the system was accepted by Raytheon with agreement and understanding from MCAS Miramar to deliver the system at the end of May 2015.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Primus' Zn/Br flow battery approach provides advantages in cycle life, cost, and performance when compare to similar technologies. The advantages are summarized in Table 2-2 below.

Table 2-2: Summary of advantages of the Primus Zn/Br system.





	Conventional flow batteries	Primus Power EnergyCell	Fewer parts	Low cost	High power	High reliability	Safety
Electrodes	High contact resistance and carbon corrosion Graphite + felt: $50/kWh	High conductivity and long life Titanium: $36/kWh		✓	✓	✓	
Ion exchange membrane	Membrane is expensive and life limiting • $500 - 900/m² → $40/kWh • 5,000 – 10,000 cycles	No membrane • $0/kWh • 30,000 cycles	✓	✓	✓	✓	
Balance of plant	2 pumps, 2 tanks, 2 set of pipes Frequent chemical and volume re-balancing	1 pump, 1 tank, 1 set of pipes No re-balancing	✓	✓		✓	✓
Electrolyte cost comparison	$200-450/kWh Vanadium, depending on purity	$45/kWh		✓			
Safety: NFPA rating Health Flammability Reactivity	3 0 2 Vanadium	3 0 0					✓
Voltage, open circuit	1.4 Vanadium 1.2 Fe-based	1.8 Zinc bromide			✓		

Primus' Zn/Br battery offers higher current density when compared to similar technologies. Their electrodes can operate at 200 mA/cm^2 vs 50 mA/cm^2 of traditional Zn/Br. Primus biggest discriminator is that it eliminates two common failure mechanisms in ZnBr flow batteries (carbon electrodes and separator membranes) by using a solid titanium electrode and not requiring a membrane. This allows their cells to operate longer than tradition flow batteries without the need for replacement. Component level testing of all of the ancillary equipment and stability testing of their cells have predicted a 20 year lifespan.

Primus's battery still uses a Zn plating mechanism for its batteries. The nature of the Zn plating requires that the cells be completely discharged to prevent dendrite growth and maintain the health of the cells. This requires that the EnergyCells be periodically stripped to properly clean and maintain them. This is handled automatically by the Battery Management System and is transparent to the user. However, this requires that an EnergyCell will be periodically taken offline. The energy storage system will still operate however it will be operating less one EnergyCell reducing its energy and power capacity during those times.

One major limitation of Primus' current system is that when the system is in islanding mode the ESS operates in voltage control mode. When operating in this mode the battery is currently not capable of charging. This is currently attributed to adequate control of plating zinc on the electrodes. Primus' development and current algorithms for charging the battery depend on optimal parameters for plating uniform layers of zinc on the electrodes in the EnergyCells. When the system is in islanded mode controlling the parameters for plating zinc become more difficult and Primus has not been able to analyze this functionality to include it in the current operation of

the system. Based on discussions with Primus' engineers the capability to charge the system in islanding mode is possible but requires testing the system and validating the techniques.

The foreseeable barriers to social acceptance would rely on the fact that an energy storage unit of this size requires approximately a 60ft x 20ft of footprint to be installed. This means that the locations that would like to use and energy storage system would need the space for the installation. The containers that the system is installed with are traditional ISO containers so the visual look of the system is not abnormal. The thermal management system and the pumps within the system will make noise equivalent to an air conditioning system which is not out of the ordinary. The electrolyte for the cells contains bromine which needs to be handled appropriately. The EnergyPod contains multiple layers of spill containment which would abate many concerns for spill protection.

3 PERFORMANCE OBJECTIVES

There are five performance objectives for this demonstration and are listed in Table 3-1 below. The performance objectives were established based on early discussion with MCAS Miramar personnel and to meet particular mission scenarios for improved energy security and operational cost reductions.

Table 3-1: Summary of Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Energy Security Performance Objectives				
Islanded Duration	Islanded Duration (hours)	Meter readings from RE system, ESS, and grid power feed	Building loads are met by ESS and PV for 72hrs under controlled load conditions meeting power quality standards of IEE1547.4	Building loads were met by ESS and PV for 5 hours 10 minutes meeting power quality standards of IEE1547.4. ESS is capable of 7 hrs 10 min.
Building Load Reductions	Delta Average kWh/day usage	Meter readings from building 6311.	Building loads can be reduced by 50% through manual changing of thermostats and lighting when compared to its previous year's average for that given month.	Building loads were able to manually increased and decreased increased by 68% when compared to baseload during islanding test
Switchover Time	Time (minutes and seconds)	Clock timing from command to go into islanded mode to ESS discharging power	Time is less than hour	Switchover from Grid to Islanding was 4 minutes
Operational Cost Reduction Performance Objectives				
ESS Energy Storage Capacity	Energy Discharged in kWh	Meter reading of energy discharged by ESS	ESS is able to discharge 1MWh of energy during peak shaving cycle.	ESS was able to discharge 390kWh in the lab and 290kWh in the field
Peak Shaving	Peak Demand Reduction (kW)	Meter readings from RE system, ESS, and grid power feed	ESS is able to store energy during off peak time and discharge 250 kW during peak time to reduce peak load	ESS was able to store energy during off peak time and discharge 100kW during

			relative to historical data over similar time period.	peak time for 2 hrs and 45 min
Qualitative Performance Objectives				
Ease of Operation	Degree of ease of use	Survey	Satisfactory rating from survey results.	Survey to be issued before final report

3.1 ISLANDED DURATION

Islanding is defined as being able to intentional isolate local facility circuit from the local electric power system as defined in IEEE 1547.4. The circuit is then power by the operation of the ESS, and RE. The Islanded duration will be the time that the system is commanded into islanded mode to the time that the system can no longer sustain the loads of the circuit.

Purpose

The purpose of the Islanding objective is to demonstrate the applicability of an isolated utility circuit going off-grid. This is useful in the case of an extreme event that could disrupt commercial utility power supply. Emergency back-up operations can be maintained by operating off of RE and an ESS if the load required is maintained within acceptable operation levels of the PV system and ESS.

Metric

The metric used for the Islanded Duration objective is islanding time measured in hours and minutes. The islanding time starts when the system is commanded to go into islanding mode from the IPEM controller. The islanding time stops when the loads can no longer be met due to the ESS being depleted.

Data

The data that will be required to calculate this metric is a multitude of measurements from various sensors within the system.

1. Power output from the PV system
2. Load data from building 6311
3. Net Power output from the ESS (Battery output minus auxiliary power including: pumps, power electronics, inverter, chiller, and heaters)
4. State of Charge of the ESS
5. Power quality measurements of the power provided to 6311
6. Clocked time showing the start of islanded operations to the end of islanded operations

Metering points for the islanding tests are shown in Figure 2-10 and in more detail in Figure 3-1 below. In addition to the metering data that is collected by the IPEM system, two independent power analyzers were connected to the Building 6311 feeder breaker and the P196 Carport PV system to collect detailed data for analysis to IEEE 1547.4 requirements.

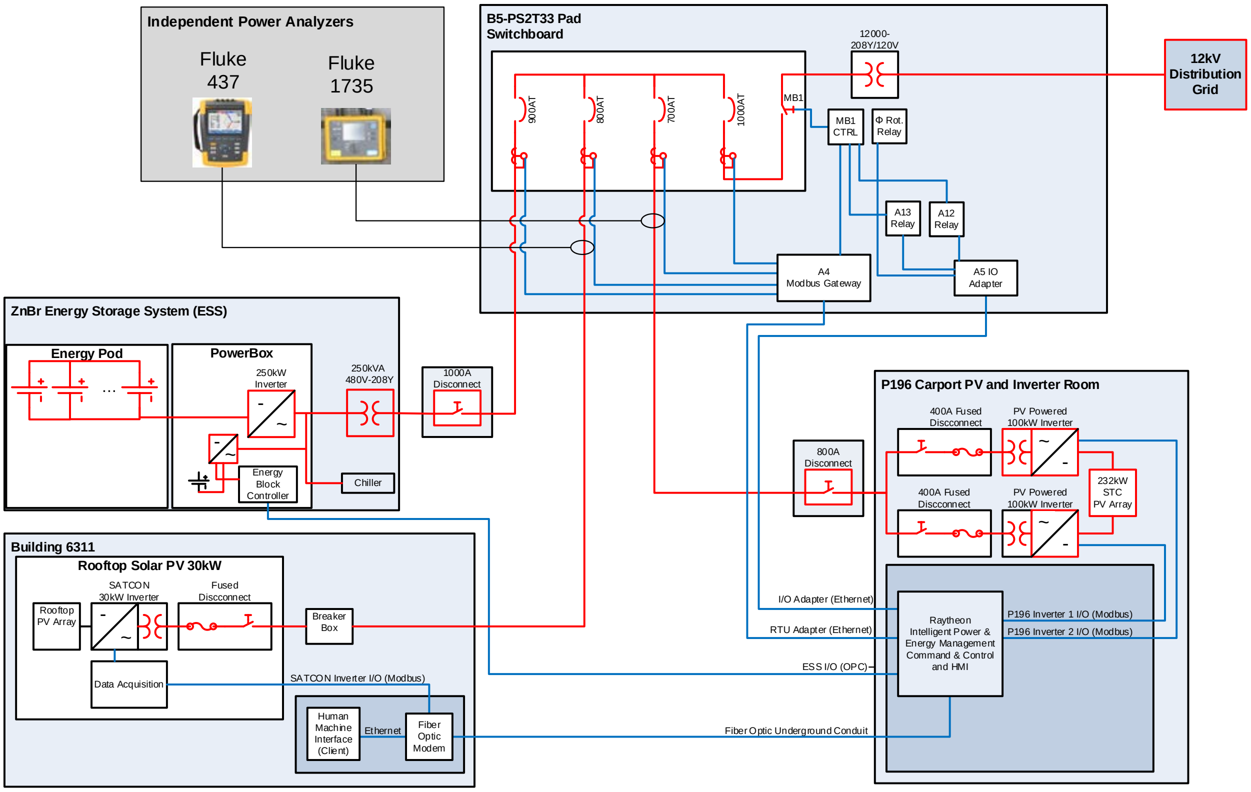


Figure 3-1: Detailed interconnect diagram for the Islanding test setup

The time elapsed will be measured from when the system is commanded to enter into islanded mode. While operating in islanded mode the various subsystems will be monitored and data will be collected on the PV system, the ESS, and the building loads. Once the battery is depleted the system will shut down until grid power is restored. After power is restored the various load data and performance data on each of the subsystem will be collected and analyzed to assess the behavior and stability of the circuit.

Success Criteria

The success criteria for this performance objective was that building loads would be met by the ESS and PV for at least 72hrs under controlled load conditions meeting power quality standards of IEE1547.4.

3.2 BUILDING LOAD REDUCTIONS

The building load reduction Performance Objective is defined as the percentage of load that has been reduced during an islanded event as compared to the previous year's average for that given month during normal grid connection.

Purpose

The purpose of this Performance Objective is to characterize the amount of building load reduction during an islanded event required in order to meet the 72hr islanded objective.

Metric

The metric for this Performance Objective is the percentage difference in kilo-watt hours per day (kWh/day) of the load when operating in islanded mode compared to an equivalent load profile for the same given month.

Data

The data required for this is the load data measured for building 6311. The following Equation 1 will be used in analyzing the data.

$$1 - \left(\frac{\int L_{island}}{\int L_{historical}}\right) * 100 \qquad (1)$$

Where L_{island} is the load data for the time during islanded and $L_{historical}$ is the historical load for the previous year's average for the same given month. The result will be the percentage of load reductions required during the islanded event.

Success Criteria

The success criteria for this objective is that building loads can be reduced by 50% through manual changing of thermostats and lighting when compared to its previous year's average for that given month.

3.3 SWITCHOVER TIME

The Switchover Time defined as the time required to switch the system from its grid transition mode (i.e. standby during grid outage) into islanded mode.

Purpose

The purpose is to characterize the timeline for islanded operations.

Metric

The metric used for this Performance Objective is time measured in minutes and seconds.

Data

The data required is the time recorded for when the system is commanded to go into islanded mode and the time recorded when the ESS begins to discharge. The time recorded for when the ESS begins to discharge will be subtracted from the time recorded for when the system was commanded to go into islanded mode. The result will be the Switchover Time.

Success Criteria

The success criteria for this Performance Objective was defined to be less than 1 hour.

3.4 PEAK SHAVING

Peak Shaving is defined as being able to arbitrage power stored from off-peak to on-peak periods. This allows a facility to load shift in order to reduce the facilities demand charges. The ESS is charged and discharged in order to change its demand load profile seen by the utility company as shown in Figure 3-2. This is useful for facilities that are on a tiered pricing scheme and/or are hit with high charges of energy use during hours of peak operation. The ESS can charge during off

peak times at a lower cost and discharge during peak hours reducing the peak loads required by a facility.

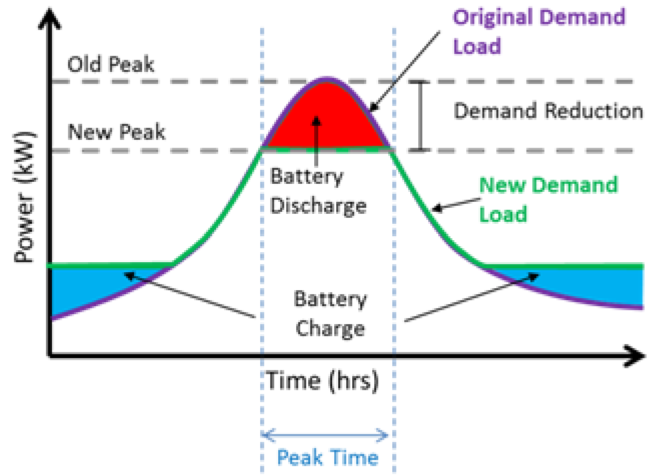


Figure 3-2: Graph showing a very simple hypothetical load profile. The purple line represents the historical load profile. The green line represents the load profile using an ESS to charge at night and discharge during the peak time of day

For many commercial and industrial facilities the cost of electricity can be heavily determined by the amount of peak power that a facility uses during a billing period. The largest peak power demand, typically for a minimum of 15 minutes, will dictate how much the facility is charged for that billing period. Different utility companies have different demand charge rate structures. Some utilities are so congested during peak times that they have a defined peak time period during the day where they charge a higher demand rate then off-peak periods. Utilities that have this type of rate structure also usually have incentive programs or mandatory demand response programs where the facility can volunteer to participate or be directed to participate in load shedding during seasonal peak times. Some utilities have a blanket demand charge that is based on the highest 15 min peak demand for a given billing month regardless of peak times. Controllable peak shaving can provide a facility with flexibility to reduce its peak demand depending on its rate structure.

SDGE has different types of rate structures for commercial/industrial facilities (Figure 3-3). One rate structure is a TOU structure that has two types of demand charges. The first is an On-Peak Period Demand Charge which is based on the 15 minute average Maximum On-Peak Period Demand. The second is the Non-Coincident Demand Charge which is based on the higher of the Maximum Monthly Demand or 50% of the Maximum Annual Demand.

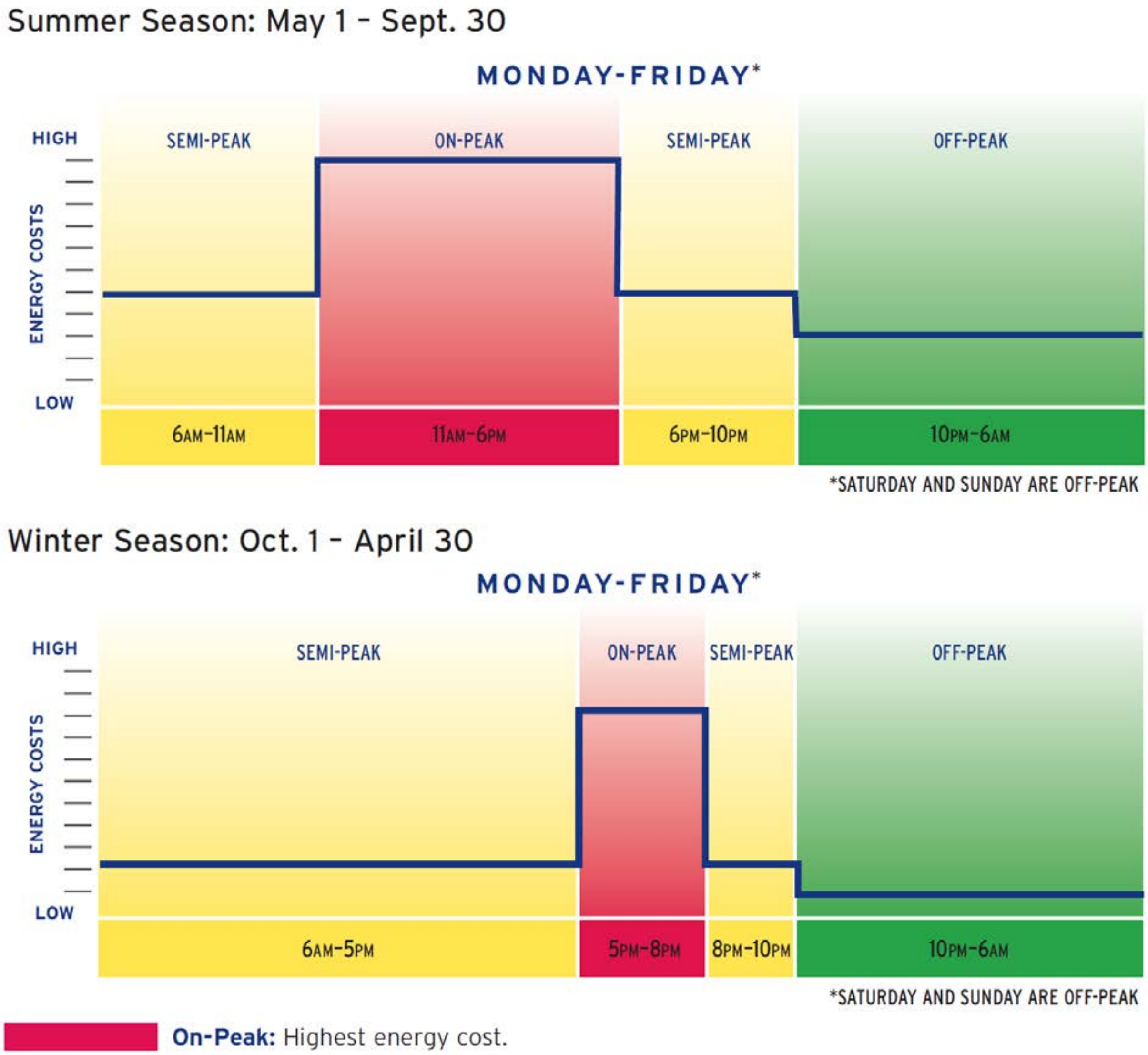


Figure 3-3: SDGE Time of Use Rate time periods.

For facilities that have TOU demand charge structure a basic peak shaving schedule is useful and can change a facilities demand load profile. Also facilities that are subject to demand response programs could benefit from this type of peak shaving mode. Currently Marine Corps pays a flat rate to NAVFAC for each kWh of energy consumed therefore the Marine Corps does not have a TOU rate structure however NAVFAC. NAVFAC is a direct customer to SDG&E and is subject to demand charges and TOU structure which is aggregated across multiple bases in the southwest and a flat normalized rate is applied to those facilities. While the Marie Corps is not subject to SDG&E’s TOU structure it does influence the rate applied to them so it is utilized in our Peak Shaving performance objective.

Metric

The metric used for the Peak Shaving objective is the difference in demand load between a relevant historical load profile and a load profile seen by the feeder meter at B5PS2T3 switchgear when

using the ESS in peak shaving mode. The metric is measured in kW and represents the amount of peak shaving achieved by using the ESS.

Data

There are two pieces of data required to calculate the Peak Shaving metric. The first is relevant historical load profile data. This data was collected a couple days prior to using the ESS in peak shaving mode. The second piece of data is the load profile when using the ESS in its peak shaving mode. The metering points for the load was collected at the B5PS2T3 switch gear according to the CT locations defined in Figure 2-10.

Success Criteria

The success criteria for this metric was originally determined to be that the ESS is able to store energy during off peak time and discharge 250 kW during peak time to reduce peak load relative to historical data over similar time period.

3.5 ESS ENERGY STORAGE CAPACITY

This Performance Objective (PO) measures the energy storage capacity of the ESS when operating in grid connected operations. The purpose of this Performance Objective is to show that the energy capacity of the energy storage system meets its rated 1MWh capacity.

Metric

The metric used for this Performance Objective is energy in kilo-watt hours (kWh) which is a measurement of power over time. The value for this PO should range from 750kWh to 1MWh.

Data

The data required for this Performance Objective is power output of the ESS and recorded time of the power output. This was captured on two different days of performing this test. The first day captured was on 11/15/2015 and the second was captured on 11/17/2015. The measurement of power over time will be analyzed and the energy capacity of the system will be the integral of the graph from the beginning of discharge to the time that the power output of the battery reaches zero.

Success Criteria

The success of this Performance Objective was defined to be that the ESS is able to discharge 750kWh threshold and 1MWh objective of energy while in Grid connected mode.

4 FACILITY/SITE DESCRIPTION

MCAS Miramar in San Diego, CA has been selected as the host facility for this installation Figure 4-1. Miramar has a long history for installing renewable energy projects at its facility.

Figure 4-1: Birds eye view of MCAS Miramar.

A brief background of MCAS Miramar and its energy portfolio is listed below.

Electrical Utility Loads

- 14 MW Peak
- 7 MW Avg
- 5 MW Min

Renewables

- 3.2 MW Landfill Power Purchase Agreement
- 1.5 MW of Photovoltaic
- PV Parking lot lights
- 24 Solar Thermal systems including the Combat Training Tank (Pool)

Energy/Water Efficiency

- Area Wide Energy Management System (DDC)
- Advanced Metering Infrastructure
- $30M of HVAC/lighting retrofits in the past 2 years
- Reclaimed Water and smart irrigation control
- Replacement of over 1300 water fixtures in 22 buildings to low flow

Behavioral Awareness

- Unit Energy Managers
- Energy Star Portfolio Manger

For this demonstration we have selected the circuit feeding off of B5PS2T3 switchgear which feeds building 6311 and the P196 Carport PV system.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The demonstration site at MCAS Miramar is shown in Figure 4-2. The specific location at MCAS Miramar where the microgrid demonstration will occur is near building 6311 (Figure 4-3). Building 6311 is mainly an office building for the energy manager, public works, and FEAD. Since the building house the energy manager and staff, the ability to take the building offline during the islanded scenarios is easier to facilitate. The base command has endorsed the project as a major stepping stone in achieving a larger microgrid effort.

The project data communications is designed to be a closed loop system avoiding any DIACAP/RMF and IT platform certifications. The data that is collected within the IPEM controller and the ESS is stored locally at Miramar and can be downloaded on the base and transferred for analysis.

Figure 4-2: Map and aerial image of MCAS Miramar.

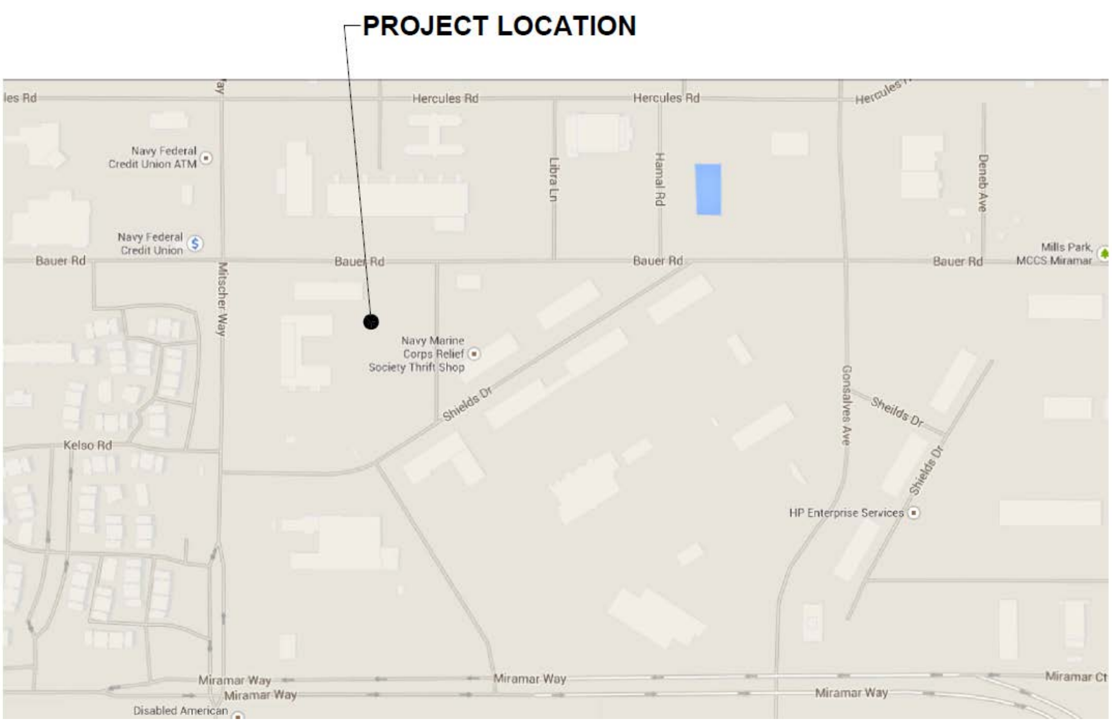


Figure 4-3: Map of the installation site at MCAS Miramar near building 6311.

The installation site for the energy storage system is under the P196 carport PV system near the inverter room as shown in Figure 4-4 below.

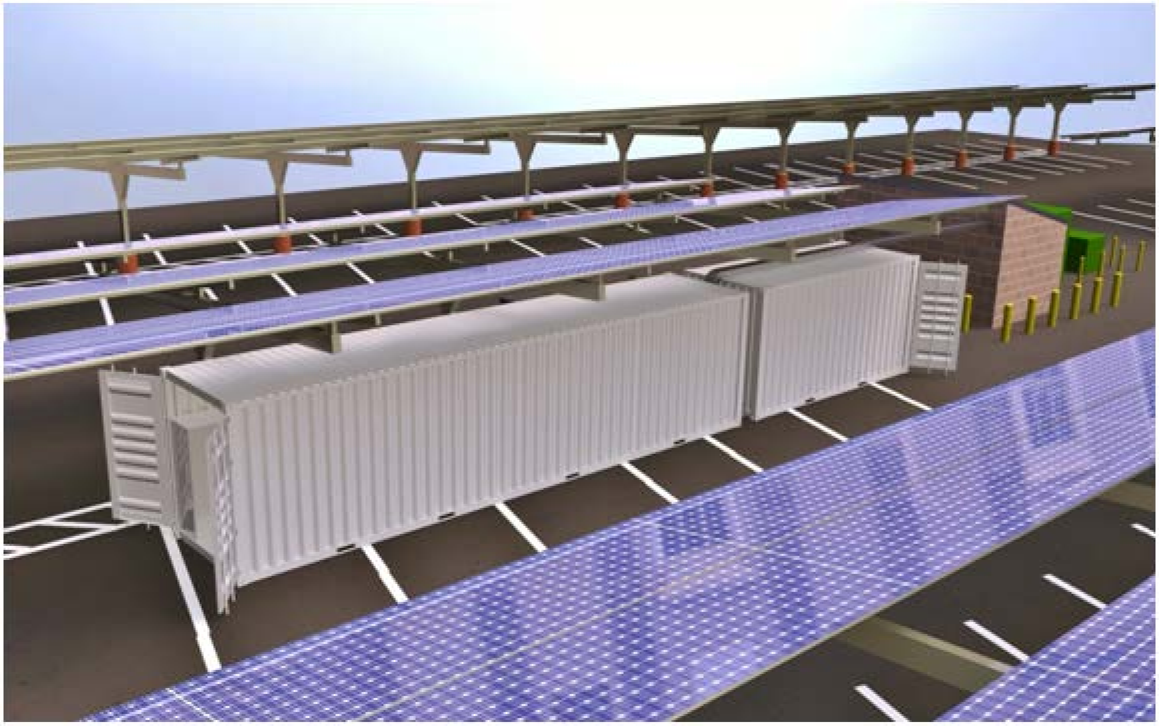


Figure 4-4: Rendering of the ESS installation site next to the P196 inverter room under the carport PV panels.

4.2 FACILITY/SITE CONDITIONS

MCAS Miramar is located in a mild climate zone in southern California. The location provides for provides good solar irradiance for the installed PV systems. Building 6311 is a perfect location for this demonstration since it has its own switchgear with 230kW of PV attached to it. The switchgear allows isolation of the circuit for islanding and the PV system allows the integration of renewable energy into the circuit when operating in islanded mode.

Many southwestern installations have large amounts of PV installed on their facilities and many are subject to similar Interconnect Agreements and UL1741 anti-islanding restrictions. This demonstration at Miramar helps prove out the capability to use energy storage in a microgrid application for integrating renewable energy systems when in islanded mode.

5 TEST DESIGN

This goal of this demonstration is to solve two main problems. The first problem is that DoD facilities are vulnerable to grid outages due to extreme events and limited to non-renewable back-up systems such as diesel generators which are regulated and can-not be used for cost reduction applications such as peak shaving. The second is that the peak electrical loads of many DoD facilities loads occur during higher rate periods incurring significant costs associated with demand charges. The demonstration aims to answer the question: “How can an ESS, coupled with an advanced control system, provide energy security while reducing overall facility energy costs?”

5.1 CONCEPTUAL TEST DESIGN

The ZnBr Installation is comprised of a ZnBr ESS integrated into the MCAS Miramar utility infrastructure which includes a 230kW carport PV subsystem and a 30kW rooftop PV subsystem. The ESS and the PV subsystems are controlled by the IPEM microgrid controller which also controls and monitors the load demand and power quality required by the MCAS infrastructure, the status and power generation of the PV system, and the State of Health (SoH) of the ESS (See Figure 5-1).

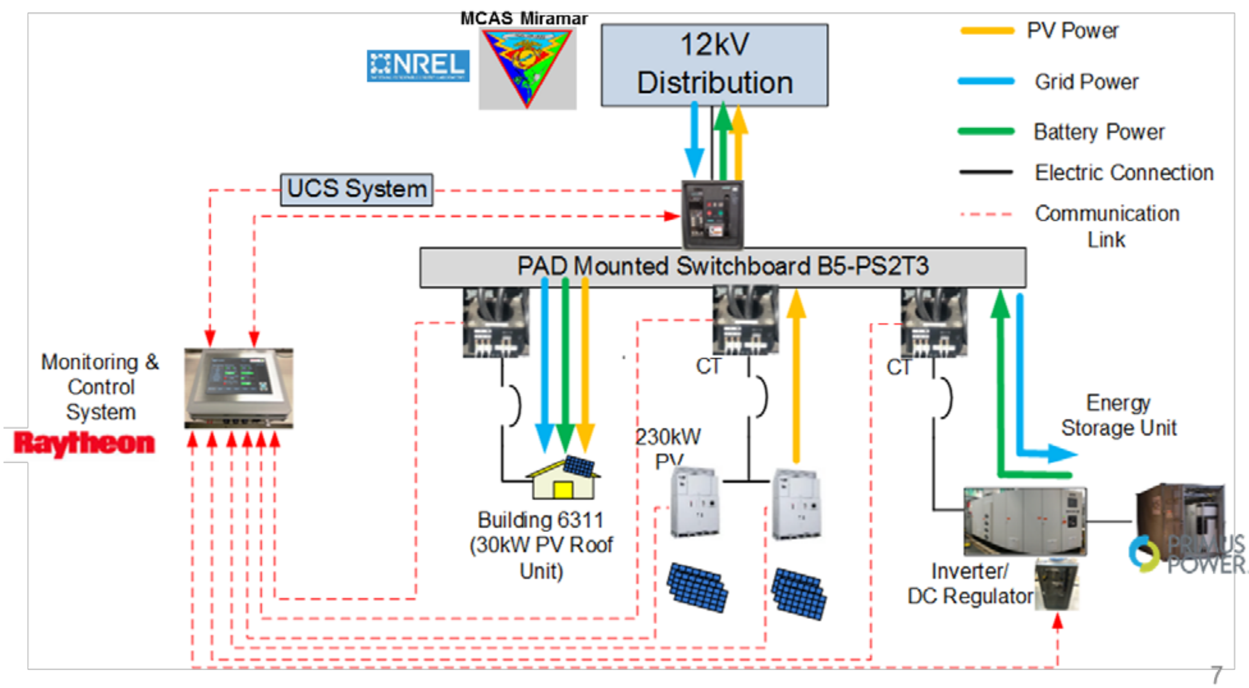


Figure 5-1: Interconnect diagram of Zn/Br installation at MCAS Miramar.

The demonstration is intended to operate in two modes 1) Islanded and 2) Peak Shaving. The islanding mode demonstrates the Islanded Operations performance objectives and the peak shaving mode demonstrates the Peak Shaving performance objectives.

The primary mission for the ZnBr Installation is to provide emergency power in the case of a grid outage. Maximizing the use of the PV and the ESS is crucial to extend the operational life of the system. This allows MCAS Miramar to operate independently from the grid in the case of a physical or cyber attack, or an environmental event that would otherwise shut down facility power.

The Installation is connected to a 230kW PV system that currently exists on the B5-PS2T3 switchgear. The carport PV inverters are UL1741 certified and therefore have built in safety features that de-energize the inverters during a grid outage. This safety feature is enabled so as to avoid inadvertently back feeding a circuit that may have a transmission wire down or a technician working upstream on the circuit. In order to meet islanding duration goals in Islanding Mode these inverters need to be active to supplement the ZnBr battery in providing power to the Miramar load. To accomplish this, the PV inverters require a firm voltage source present in order to activate and synchronize. The ESS provides this voltage source for the islanded system maintaining voltage regulation of the circuit. During this mode, the circuit is isolated from the rest of Miramar's distribution system with the installation of a remote operated Main Breaker at the point of common coupling, replacing the existing main breaker on the B5PS2T3 switchgear. The Main Breaker opens and closes based on commands from the IPEM subsystem to isolate the circuit from the grid, thereby meeting the guidance referenced in IEEE 1547.4. Since the ESS acts as the voltage regulator for the system, it does not currently have the capability of charging while in Islanding Mode as part of its current control software. Precise control of the zinc plating process is required for the energy cells to operate efficiently. When operating in voltage control mode, Primus Power has not fully developed the control systems and algorithms to monitor and maintain uniform zinc plating that switches from charge to discharge quickly. While the basic principle of rapid discharge and charge has been demonstrated the software and real time controller code has not been developed therefore this is a current limitation of the system utilized in this demonstration.

The average peak load for building 6311 on the base is 61kW with a highest peak of 113kW. Figure 5-2 shows the average load profile for building 6311 for each month of the year.

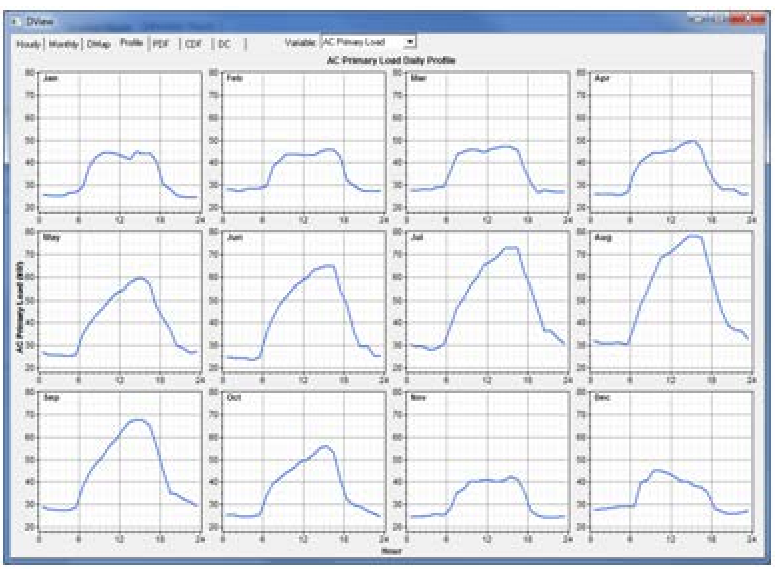


Figure 5-2: Average daily load profiles by month for building 6311 at MCAS Miramar.

The average daily PV Output for the P196 Carport PV subsystem is shown in Figure 5-3 below for each month. Data for the month end of September was unavailable but is assumed to be similar to the months of August and October.

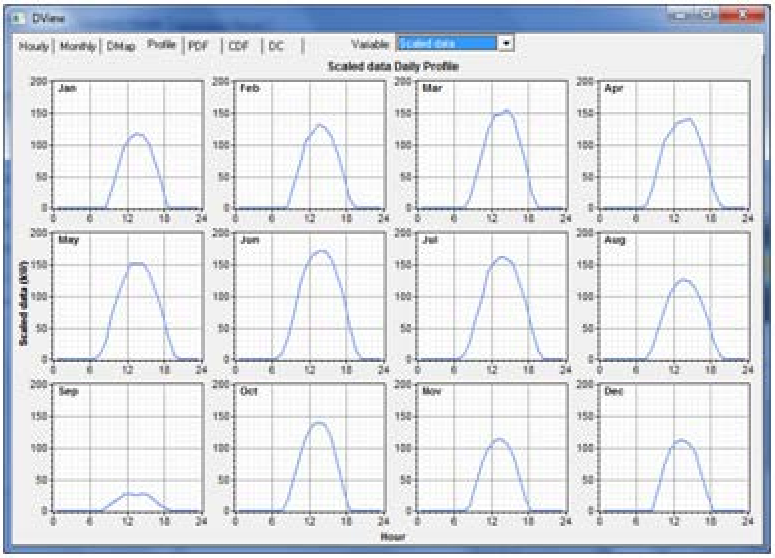


Figure 5-3: Average daily power output of the P196 carport PV subsystem.

Based on the data the P196 PV subsystem generates more power output than building 6311 requires. Because the ESS does not currently have the capability to charge when operating in voltage control mode and the PV system generates more than the 6311 load, control of the P196 subsystem is required in order to make sure that more power is not generated than is required during islanding mode. Typical commercial PV inverters are not capable of being actively curtailed, however the two Advanced Energy inverters that are part of the P196 subsystem were capable of being enhanced to provide this capability. Raytheon had the two inverters upgraded with new communication cards and firmware to add a curtailment function to their Modbus interface.

During islanded operation, the IPEM microgrid controller controls the curtailment set point of the PV Inverters in order to keep the power generated by the PV below the demand required by the building. The ESS provides the remaining power delta between what the PV generates and the required power to meet the load. An example of this behavior is shown in Figure 5-4 below.

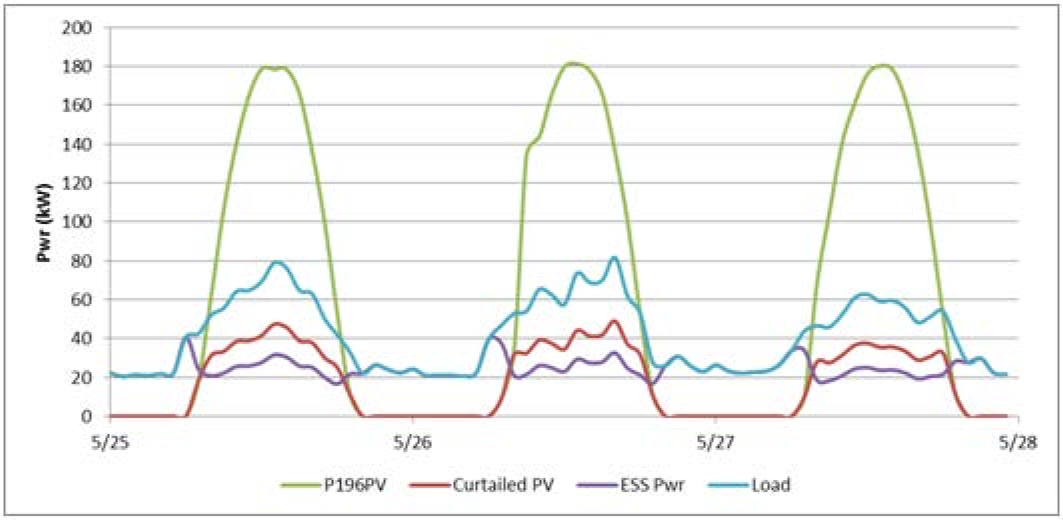


Figure 5-4: Simulated load and power output profile for the ZnBr installation during islanded operation.

The green line in the plot shows what the normal power output capacity of the P196 carport PV subsystem can achieve. The red line shows what the power output capacity of the P196 carport PV subsystem is predicted to be once controlled by the IPEM subsystem. The power output is controlled (or curtailed) to always remain below the load. Prior to starting the program it was unknown as to the amount that the PV would need to be curtailed because it was dependent on the capabilities of the power electronics within ESS, capabilities of the IPEM controller, the response time of the AE inverters and the behavior of the Miramar load. Each one of these elements required detailed modelling, analysis and testing to validate the proper functional behavior required to make them work together. Early analysis of the microgrid showed that Islanding duration is directly related to 3 main factors;

1. Battery Energy Capacity: A fixed value based on the amount of energy capable of being stored in the ESS.
2. PV Penetration: Defined as the ratio of $\left[\frac{PV\ Power\ Generated}{6311\ Load} * 100\right]$. This is limited by ability for curtailment function in the AE inverters to respond to large drops in load and stability of battery inverter
3. 6311 Load Management: The ability to be able
    a. The largest loads within 6311 are due to Cooling and Interior Lighting (~54%)
    b. Currently only method for reducing HVAC cooling loads is manual adjustments of thermostats

In order to achieve the 72 hr islanding time duration then a combination of high PV penetration levels and load reductions would be required.

Table 5-1: Table showing the relationship between PV Penetration, Load Reductions and its effect on Islanded Duration.

		Load Reduction Percentage								
		34%	36%	38%	40%	42%	44%	46%	48%	50%
PV Penetration % (to Load)	90%	73	75	79	80	84	87	91	94	98
	85%	-	72	75	78	80	83	86	91	94
	80%	-	-	72	74	76	78	82	86	91
	75%	-	-	-	-	73	76	80	83	87
	70%	-	-	-	-	-	72	76	79	82
	65%	-	-	-	-	-	-	73	76	78
	60%	-	-	Islanding Time (Hrs)				-	74	76
	55%	-	-					-	-	73

The culmination of the design and analysis of the curtailment functionality was when the system was tested at NREL in December of 2014. This was the first opportunity for bringing together all of the major subsystems of the microgrid together.

The load profile for building 6311 at Miramar consists of both real and reactive power components. The reactive component of the Miramar load is mainly due to motor loads from its environmental controls (heating and air conditioning). A plot of building 6311's load profile including the real and reactive power components is shown in Figure 5-5.

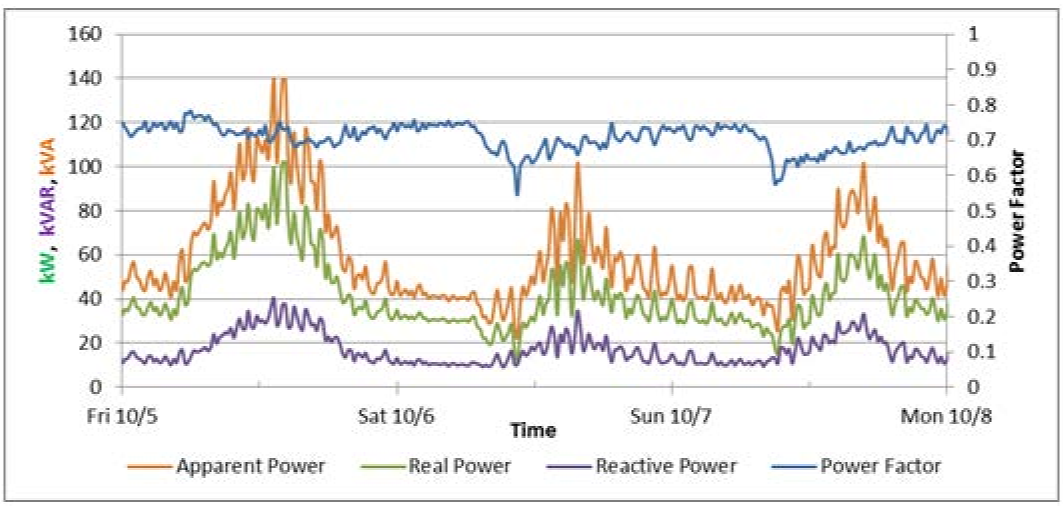


Figure 5-5: Load profile for building 6311 including real, reactive and apparent power as a function of time. The data was sampled at 15 minute intervals. The power factor is plotted on the secondary axis.

As result of the load consisting of a reactive power component power factor needs to be taken into consideration when managing the PV load. The variable nature of PV production and motor loads creates transient conditions that require accommodation by the power electronics of the ESS. Therefore the amount of PV provided to the load needed to be balanced between the capabilities of the ESS power electronics and the transient conditions of the circuit. During the course of developing and testing the system it was also determined that the power electronics within ESS

require approximately 10kW of power output to maintain the control loops utilized in managing the battery's DC bus.

The second mode of the demonstration is to demonstrate the capability for an ESS to allow a facility to reduce peaks in power usage by implementing peak shaving algorithms. This capability is provided by a controlled charge and discharge of the ESS according to a programmed or automated schedule. The result is that the load profile of grid purchases is changed in the favor of the facility in order to avoid peak demand and transmission charges. An example of this is shown in Figure 5-6 below.

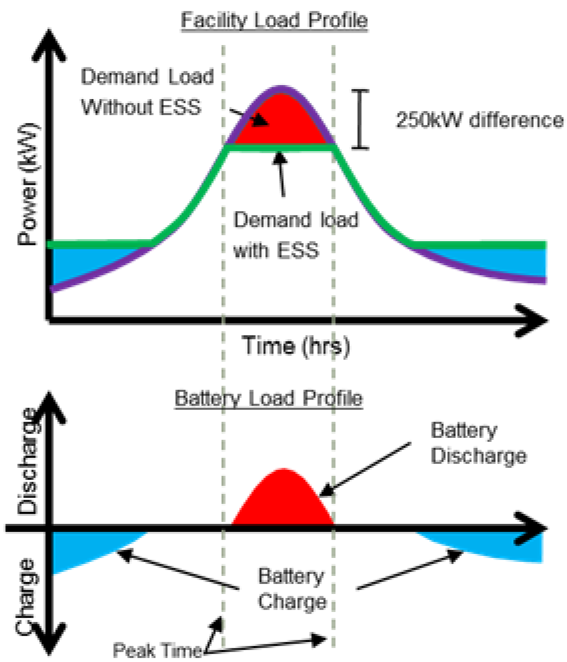


Figure 5-6: Plot showing example of how peak shaving can change the load profile of a facility as seen by the utility.

The independent variables that will be manipulated are defined below:

For Peak Shaving Mode

- Battery discharge/charge rate – The battery discharge/charge rate is the rated power that the Zn/Br flow battery will charge or discharge during peak shaving mode.
- Battery discharge/charge time – The battery discharge/charge time is the scheduled times that the Zn/Br flow battery will charge or discharge.

For Islanded Mode

- PV input curtailment – The PV input curtailment is the amount of PV that needs to be curtailed when operating in islanding mode to avoid power instability. It correlates with PV penetration of the circuit.
- Load Reduction – The load reduction is the amount of load that needs to be reduced when compared to normal operations.

The dependent variables observed for this demonstration are:

- ESS SOC – This is the current state of charge of the energy storage system
- Boot-up time of ESS – This is the amount of time it takes the ESS initialize and boot up into ready mode.
- Switch over time during blackout - This is the time it takes for the ESS to power up the circuit when commanded to go into islanded mode.
- Successful switch to Islanding mode – This is the determination of whether or not the switchover to islanding mode is successful

The controlled variables for the demonstration are

- Relative Building Load- The relative building load is the relative percentage of building load the demonstration will hold to when compared to normal operations

5.2 BASELINE CHARACTERIZATION

The baseline characterization of Miramar's building 6311 were taken in November 2015, prior to the December demonstration. The data was collected from the Advanced Metering Infrastructure (AMI) smart meters that are installed in the B5PS2T3 switchgear.

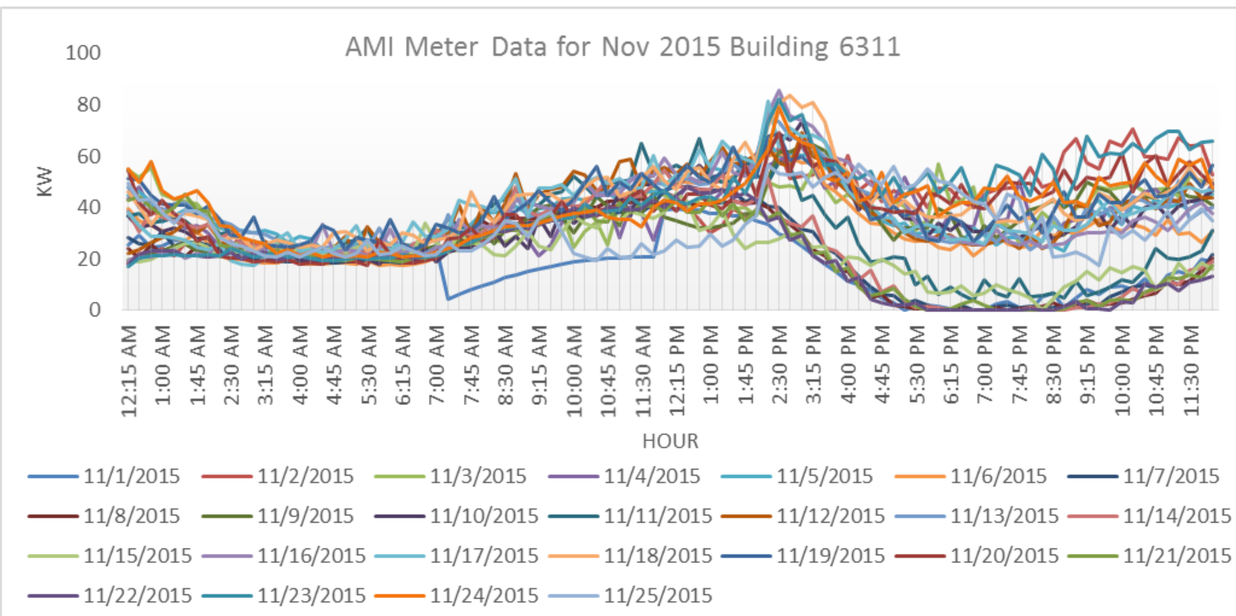


Figure 5-7: Daily load profiles for building 6311 during November 2015.

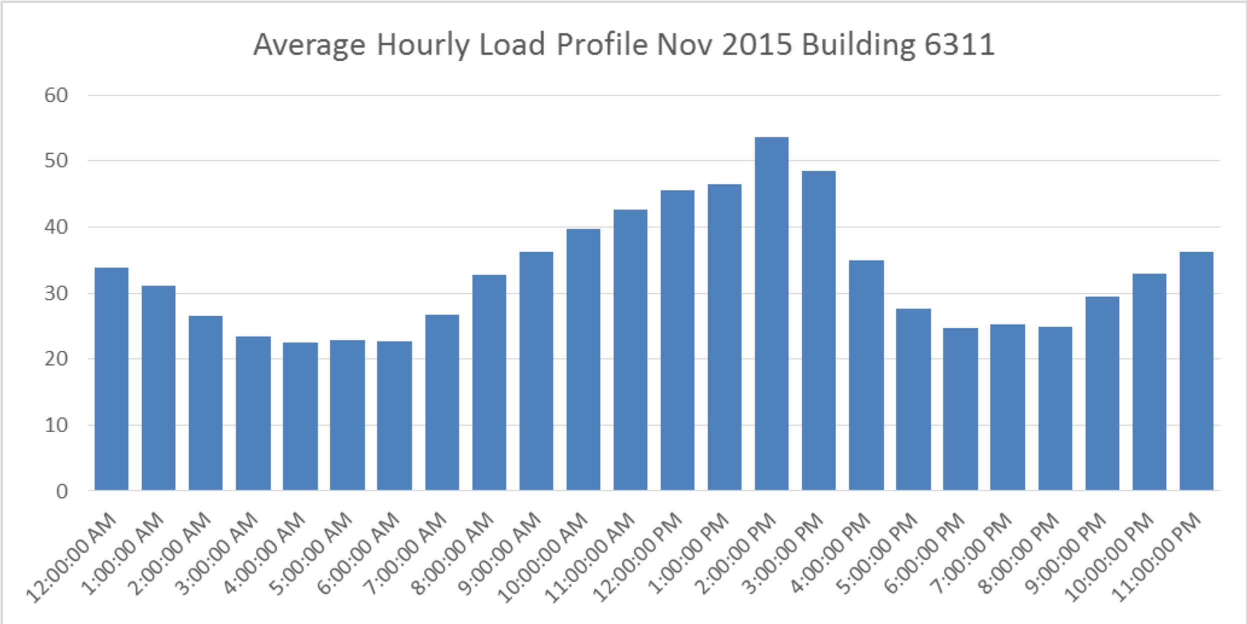


Figure 5-8: Average hourly load profile for building 6311 during November 2015.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

This demonstration consist of four significant technology elements and they are; 1) The ZnBr ESS 2) The IPEM Microgrid Controller 3) The Switchgear 4) The PV Inverters. The locations and layouts of each element are shown in Figure 5-9 below.

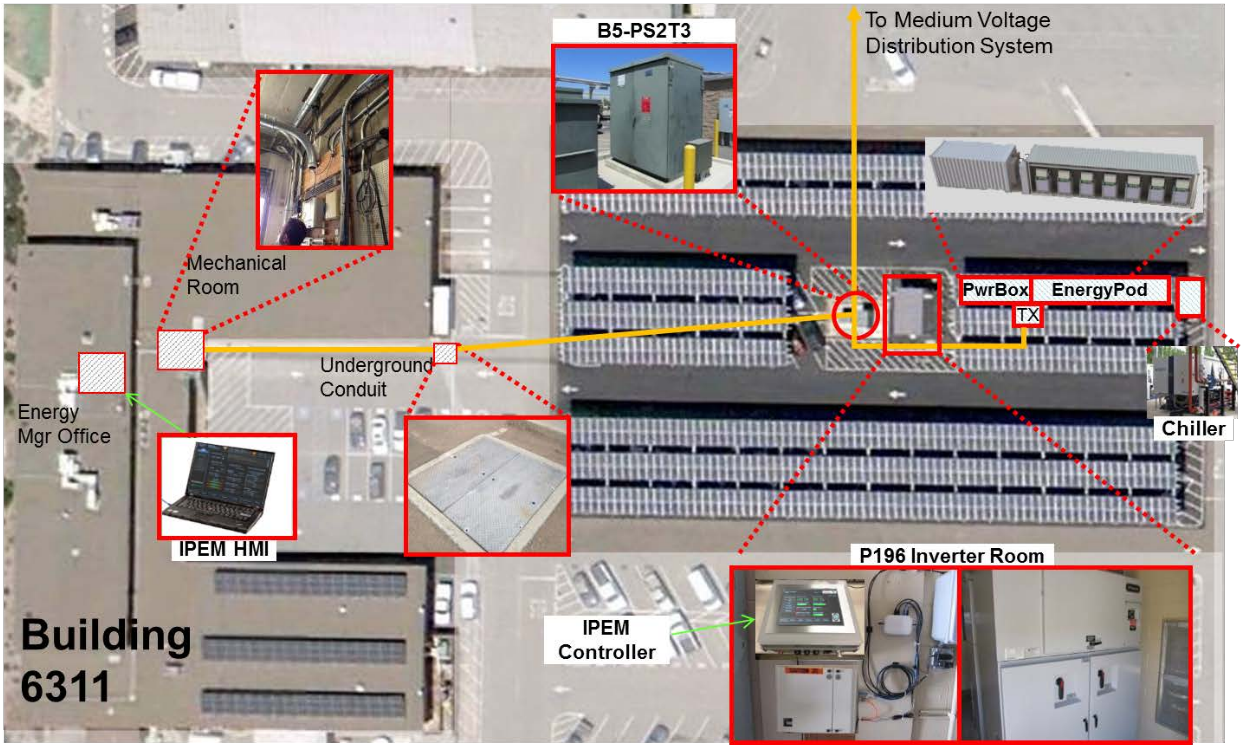


Figure 5-9: Birds eye view of MCAS Miramar site and layout of system components.

ZnBr Flow Battery

Primus' ZnBr battery was delivered and installed on May 2015. Pictures of the battery being delivered are shown in Figure 5-10 below.

Figure 5-10: Photos of the Primus ESS being delivered to MCAS Miramar. The EnergyPod need to have a large crane in order to lift it off of the delivery truck.

The ESS location is positioned in the parking lot of building 6311 next to the P196 inverter room and under one of the carport solar panel locations.

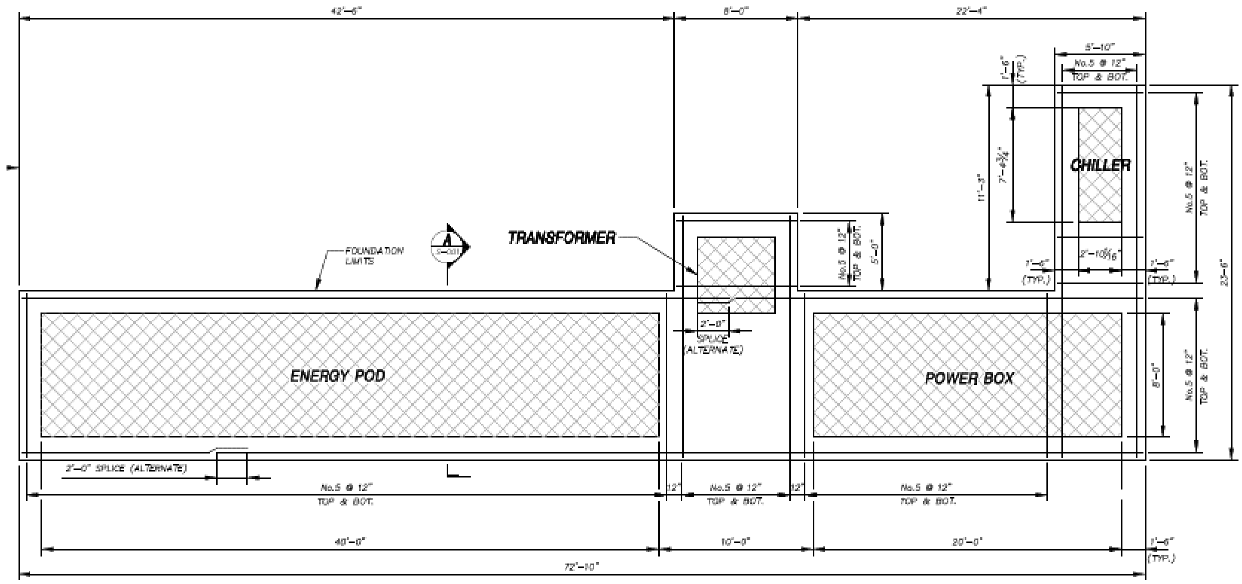


Figure 5-11: Construction drawing schematic of ESS location.

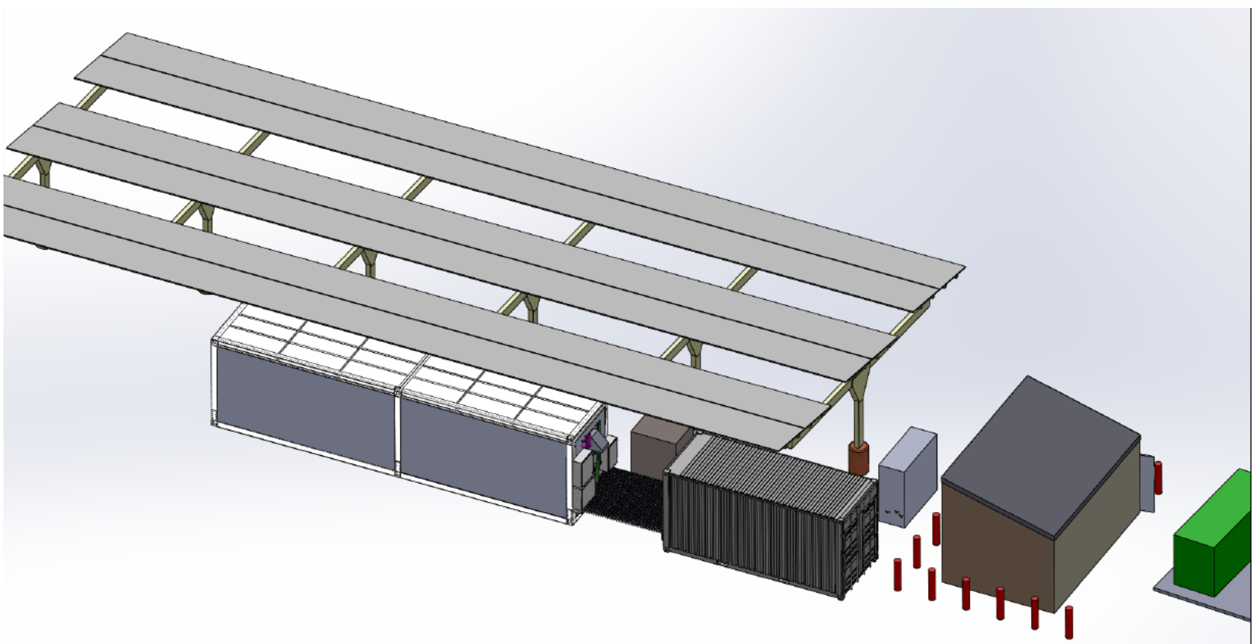


Figure 5-12: 3D CAD image of the ESS location.

IPEM Microgrid Controller

Data collection, analysis and system control forms the backbone of IPEM. Performance modeling and simulation is performed on the system configuration to generate a baseline of data to reference and optimize from. Optimized C2 code generated from simulation is loaded to the controller board. The IPEM controller is the central process and decision making device which provides supervisory control of all subsystems. The controller then uses the live data collected from the subsystems and other ancillary sensors to dynamically optimize the holistic performance of the energy system. Live and historical system status is provided to an operator via the HMI display. The HMI display

allows a user to switch between system modes and tailor the system performance based on user desired parameters. The HMI provides a user with a high level system state display as well as low level operating parameters for each component.

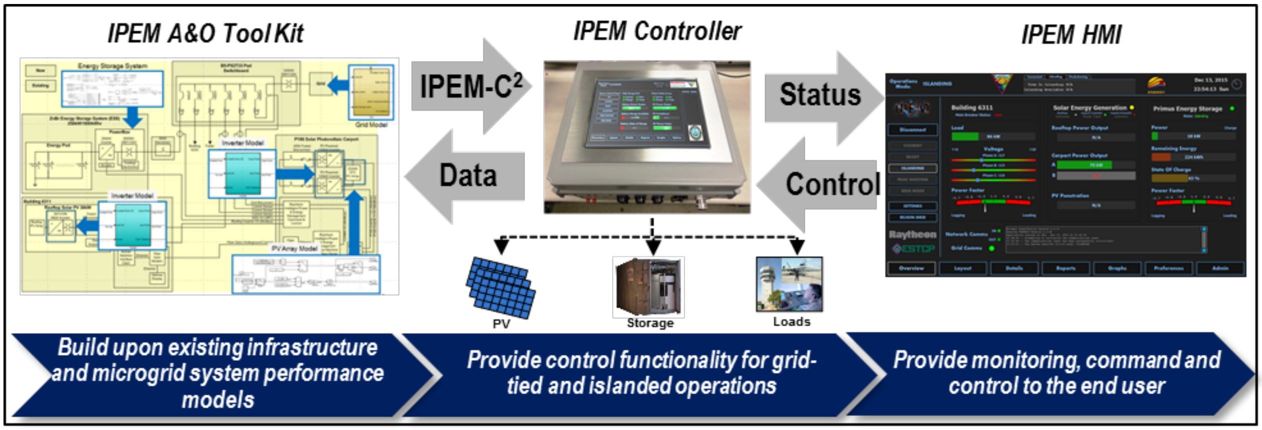


Figure 5-13: IPEM command and control suite.

The IPEM controller is located inside the P196 inverter room on the west wall. Images of the IPEM controller as it was installed are shown in Figure 5-14 below.

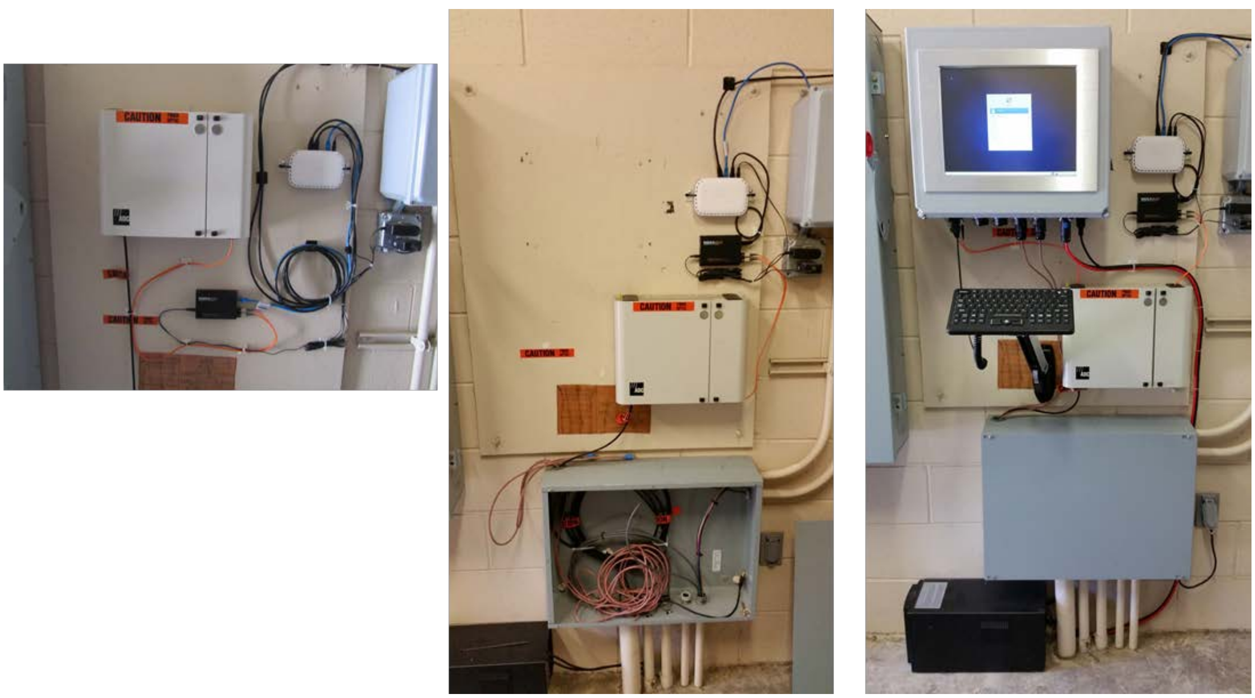


Figure 5-14: Photos of inside the P196 inverter room where the IPEM controller was installed. The image on the left shows the location pre IPEM. The middle image shows some of the existing fiber termination block and equipment moved to accommodate the IPEM controller. The right image shows the IPEM controller and ancillary equipment installed.

The IPEM HMI is utilized for system control and monitoring. Throughout operation, performance against both technical objectives can be monitored via visual display of the system operation. This dashboard style interface displays the live data from all of the various system components that the

controller is monitoring. Status of the system is easily identified through the use of indicators and gauges (as shown in Figure 5-15).

Figure 5-15: Screen shots of the IPEM HMI .

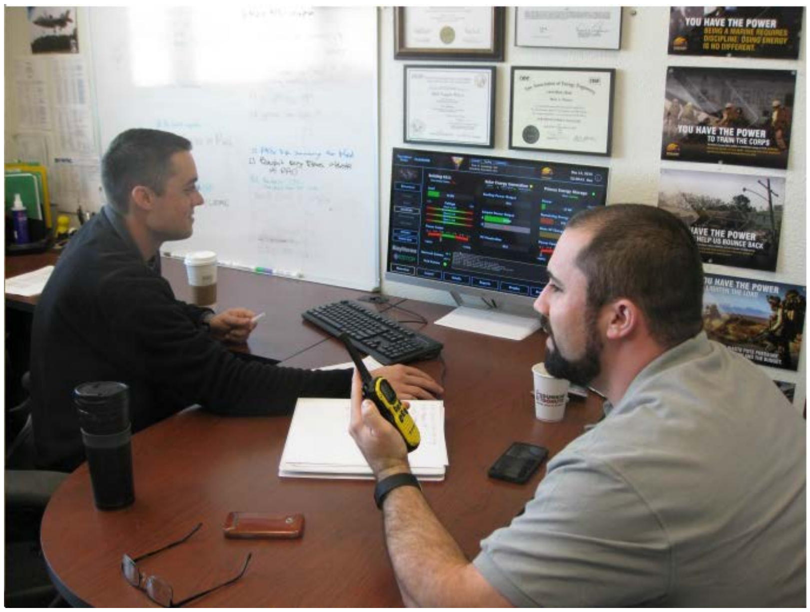


Figure 5-16: Photo of IPEM HMI being utilized on 12/13/15 islanding demonstration.

5.4 OPERATIONAL TESTING

Testing of the microgrid including the demonstrations was divided into three phases of test: 1) System Initialization and Checkout 2) Grid Tied Mode and 3) Islanded Mode. Each phase of testing is described in more detail below.

System Initialization Checkout

System Installation, Integration, and Checkout is anticipated to consist of emplacement/installation, interconnection (power and communication), and verification of operation and communication of the equipment described in Section 7 prior to test start. This will include verification of communications interfaces between various items. Emplacement/installation and interconnect will be completed by NREL, Primus Power, or Raytheon as indicated in Table 5-2. Communications interfaces between various items will be verified by Raytheon, Primus Power and Advanced Energy (AE) in the week prior to test start. Checkout is considered complete when each item is operational and communication between each item has been established.

Grid-Tied Mode

The purpose of Grid-Tied Testing is to demonstrate the system is properly configured and functionally capable of meeting the performance objectives in Table 5-2.

Table 5-2: Grid Tied Performance Objectives for ESTCP Demonstration

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Peak Shaving	Peak Demand Reduction (kW)	Meter readings from RE system, ESS, and grid power feed	ESS is able to store energy during off peak time and discharge 250 kW during

			peak time to reduce peak load relative to historical data over similar time period.
ESS Energy Storage Capacity	Energy Discharged in kWh	Meter reading of energy discharged by ESS	ESS is able to discharge 1MWh of energy during peak shaving cycle.

Grid Tied Mode testing will achieve the following objectives:

1) Verify integrated system functionality and monitoring/fault detection functions of IPEM Controller in the presence of real PV source and load characteristics
2) Validate scheduled peak shaving functionality in grid-tied mode in the presence of real PV source and load characteristics

Islanded Mode

The purpose of Islanded Mode Testing is to demonstrate the system is properly configured and capable of meeting the performance objectives in Table 5-3.

Table 5-3: Islanded Mode Performance Objectives for ESTCP Demonstration.

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Islanded Duration	Islanded Duration (hours)	Meter readings from RE system, ESS, and grid power feed	Building loads are met by ESS and PV for 72hrs under controlled load conditions meeting power quality standards of IEE1547.4
Building Load Reductions	Delta Average kWh/day usage	Meter readings from building 6311.	Building loads can be reduced by 50% through manual changing of thermostats and lighting when compared to its previous year's average for that given month.
Switchover Time	Time (minutes and seconds)	Clock timing from command to go into islanded mode to ESS discharging power	Time is less than hour

Islanded mode testing will achieve the following objectives:

1) Validate open transition/Black Start sequencing to commence operation in islanded/microgrid mode
2) Demonstrate load following operation with ESS-inverter voltage/frequency control in the presence of real load characteristics
3) Validate monitoring/fault detection functions of IPEM Controller in islanded mode
4) Validate PV curtailment functionality

5) Demonstrate load following operation with ESS-inverter voltage/frequency control in the presence of real load characteristics and PV
6) Evaluate system power quality (e.g., voltage, frequency, harmonics) as a function of load characteristics (e.g., transients, power factor)
7) Evaluate system power quality (e.g., voltage, frequency, harmonics) as a function of PV penetration

5.4.1 Test Configuration

The test configuration is shown in Figure 5-17.

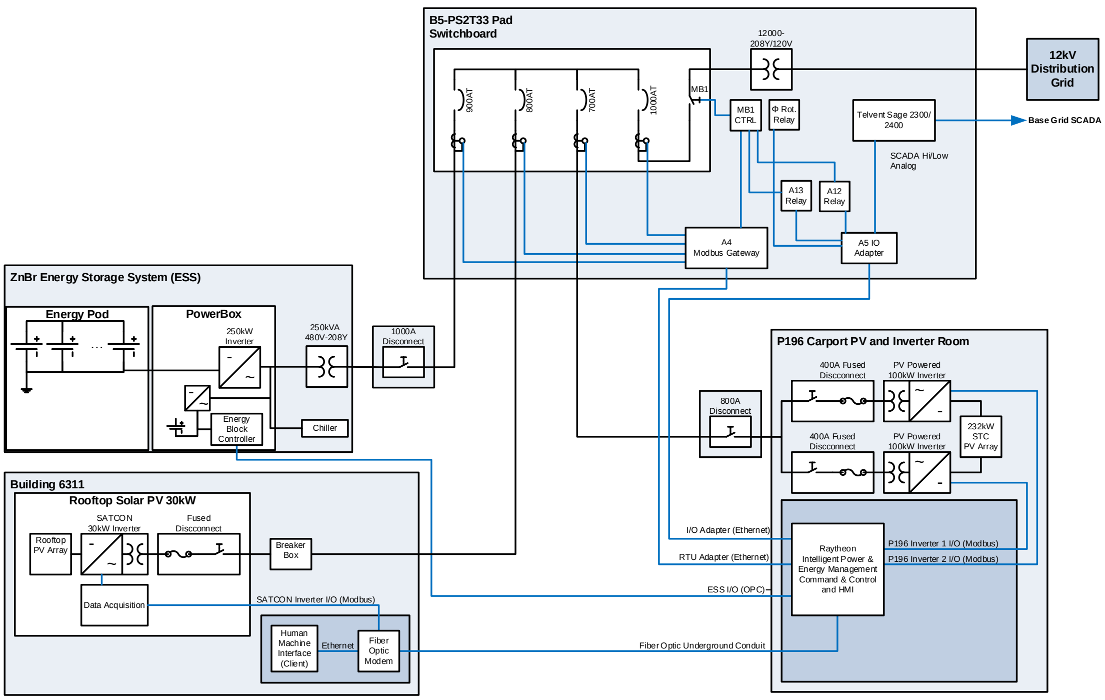


Figure 5-17: System configuration block diagram.

5.4.1.1 Equipment Involved in Testing

Table 5-4: List of equipment used in system test setup.

QTY	Equipment	Provided By	Installed By
1	Primus EnergyPod	Primus	Dynalectric
1	Primus PowerBox	Primus	Dynalectric
1	Primus Chiller	Primus	Dynalectric

QTY	Equipment	Provided By	Installed By
2	AE100TX solar inverter 100kW	Miramar	N/A
1	Satcon 30kW Solar PV Inverter	Miramar	N/A
1	250kVA 480V/208V Wye Transformer	Dynalectric	Dynalectric
1	IPEM Controller	Raytheon	Raytheon
1	New B5-PS2T33 Switchboard	Dynalectric	Dynalectric
1	Fluke 437 Series II Power Analyzer	Raytheon	Raytheon/NREL
1	Fluke 1735 Data Logger	NREL	NREL

5.4.2 System Integration and Checkout Tests

The System Integration and Checkout tests encompass the installation and methodical testing of the various subsystems as they are installed at Miramar and commissioned into a complete system. PV Communication and Curtailment Functionality Test

5.4.2.1 PV Communication and Curtailment Functionality Test

The PV Communication and Curtailment test utilizes the two AE 100TX Inverters, Miramar Utility Grid, and IPEM Controller to test the communication interface and curtailment functionality of the AE inverters (Figure 5-18). The Miramar Utility Grid is required in order to generate a stable voltage reference in order for the PV inverters to synchronize and operate.

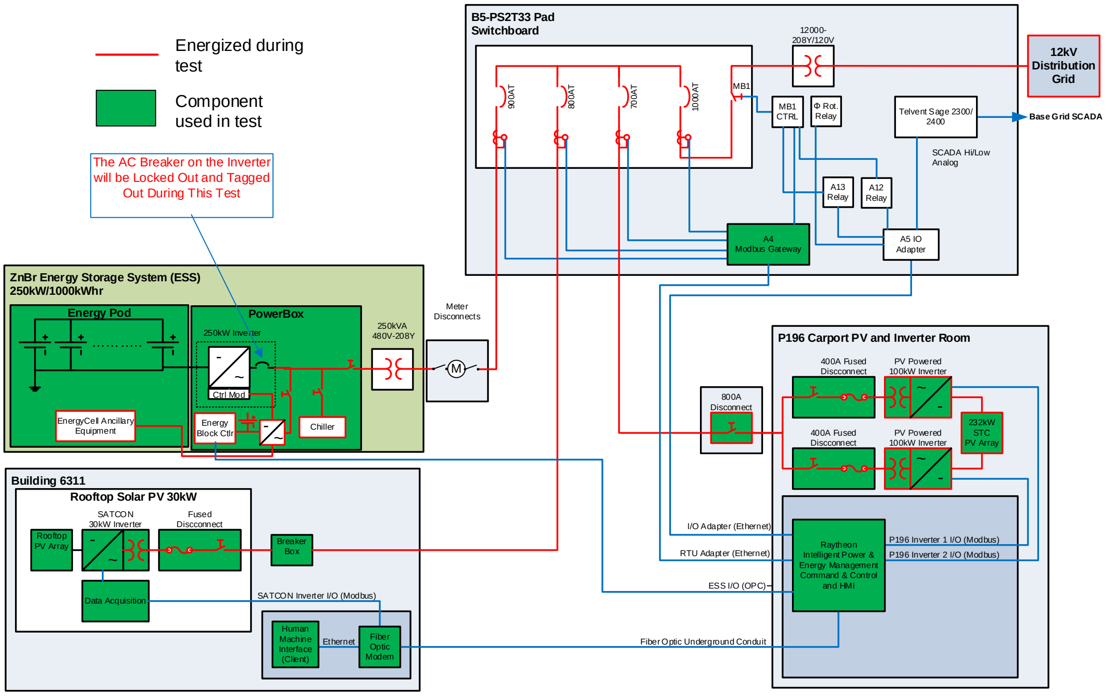


Figure 5-18: Test configuration for PV Comms and Curtailment Test

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active.
3) The two AE inverters and Satcon inverter are energized and no faults reported.
4) The ESS is in Standby Mode.

Notional Test Procedure

1) Verify nominal operation of inverters A & B using the default curtailment setting of 100%
2) Collect data (I,V,etc) from PV inverters A and B using CTs and PTs interfaced to the IPEM Controller
3) Collect data (I,V) using separate power quality analyzers
4) Reduce the curtailment setting to 10% in 10% decrements. Each setting will be maintained for a minimum of 30 seconds.
5) Increase the curtailment setting to 100% in 10% increments. Each setting will be maintained for a minimum of 30 seconds.

Results

The PV curtailment commands were properly sent and implemented on the AE Inverters and verified by the CTs in the switchgear as well within the power quality analyzers.

Item	Description of Desired Outcome	Outcome of Test
1	Verify that the PV curtailment commands resulted in the expected changes in inverter output	Complete

2	Verify agreement between IPEM Controller and power analyzer acquired data	Complete

5.4.2.2 Energy Storage Charge/Discharge Test

The Energy Storage Charge/Discharge Test utilizes Building 6311, Miramar Utility Grid, Primus Power ESS, and IPEM Controller to verify communications and control between the ESS and the IPEM Controller. The Energy Storage Charge/Discharge Test also verifies the general operability of the simulated Primus Power ESS approach. .

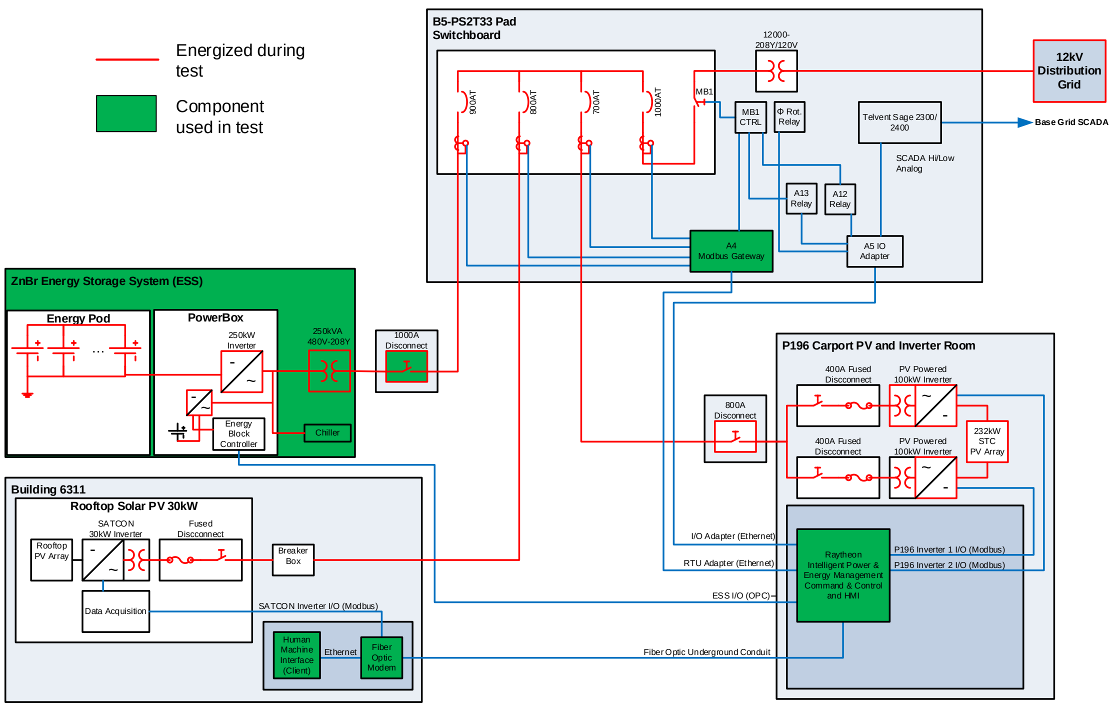


Figure 5-19: Test configuration for Energy Storage Charge/Discharge Test .

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active.
3) The ESS is in Ready State.

Notional Test Procedure

1) If ESS is less than 100% SOC then Command ESS to charge at 140 kW for until the ESS is at 100% SOC
2) Command ESS to discharge at 250 kW for 2 hrs
3) Command ESS to charge at 140 kW for 2 hrs until the ESS is at 50% SOC
4) Command IPEM Controller to step through charge/discharge profile as shown below:

kW	Time (min)	
10	1	Discharge

30	1	Discharge
50	1	Discharge
100	5	Discharge
150	5	Discharge
200	5	Discharge
250	5	Discharge
0	5	Hold
-140	1	Charge
-160	1	Charge
-180	5	Charge
-200	5	Charge
0	5	Hold

Results

Item	Description of Desired Outcome	Outcome of Test
1	Verify dataflow from IPEM Controller to Primus Power Energy Block Controller	Complete
2	Verify operation of Primus Power Energy Block Controller with Parker GTI Inverter equipped with DC pre-regulator	Complete
3	Verify ability of IPEM Controller to charge and discharge simulated Primus Power ESS upon command	Complete

5.4.3 Grid Tied Mode Tests

The Grid Tied Tests encompass a subset of tests to demonstrate the Peak Shaving capabilities of the system and test compliance with IEEE1547 and IEEE1547.1 For Grid Tied tests, the complete test setup is employed.

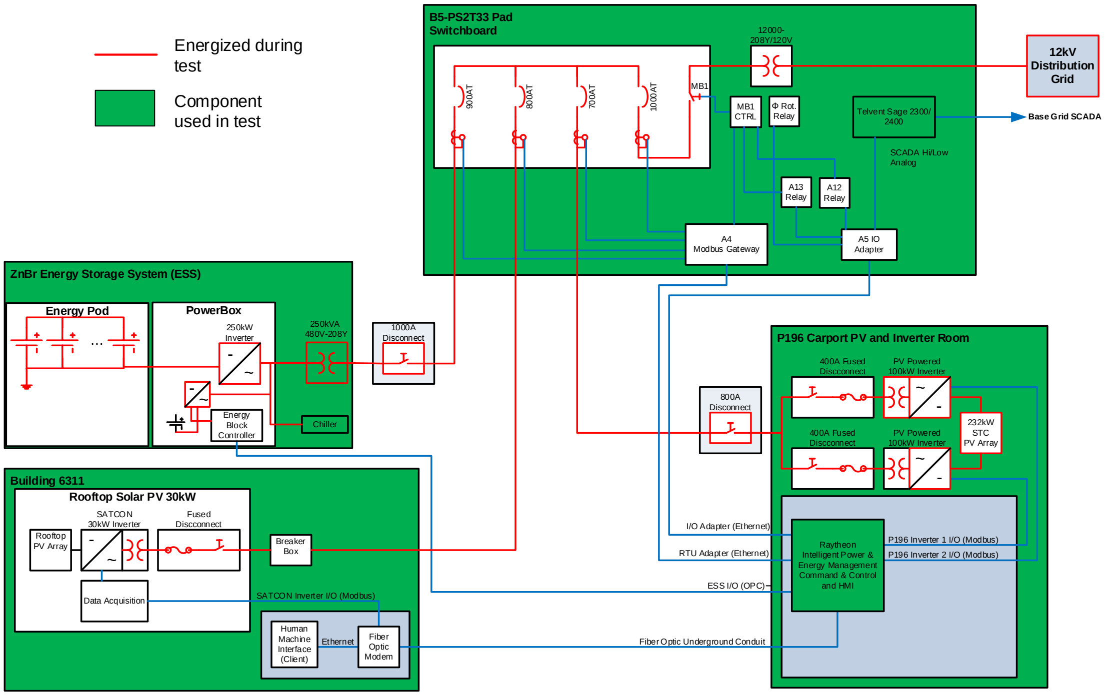


Figure 5-20: Test configuration for Islanded Mode Tests

5.4.3.1 Scheduled Peak Shaving Test

The scheduled peak shaving test demonstrates the ability of the system to execute scheduled peak shaving with the IPEM Controller directing charge and discharge of the simulated ESS

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active and the Main Breaker is Closed.
3) The ESS is in Ready State.

Notional Test Procedure

1) Check that the ESS System State is at Ready State
2) Transition system to Peak Shaving Mode via IPEM Controller
3) Verify the following sequence
    a) At a pre-determined time, the IPEM Controller directs the ESS to charge at 167kW off of the Miramar Utility Grid
    b) The IPEM Controller monitors simulated ESS SoC
    c) At a pre-determined SoC, the IPEM Controller directs the ESS to cease charging
    d) At a pre-determined time, the IPEM Controller directs the ESS to discharge at 100kW
    e) The IPEM Controller monitors the ESS SoC
4) The user returns the system to the Ready State via the IPEM HMI

Results

Item	Description of Desired Outcome	Outcome of Test
1	The system is able to charge and discharge autonomously to a pre-determined schedule and power levels via automated peak shaving control from the IPEM Controller	Complete
2	The IPEM Controller monitors ESS SoC and starts and stops charge and discharge operations in accordance targeted levels	Complete

5.4.4 Islanded Mode Tests

The Islanded Mode Tests encompass a subset of tests that step through the various stages of islanded operations. The Islanded Mode Tests are divided into three subcategories: 1) Pre-Island Conditions 2) Grid Transition and 3) Full Islanding. For the Islanded Mode Tests all equipment in the test setup is used.

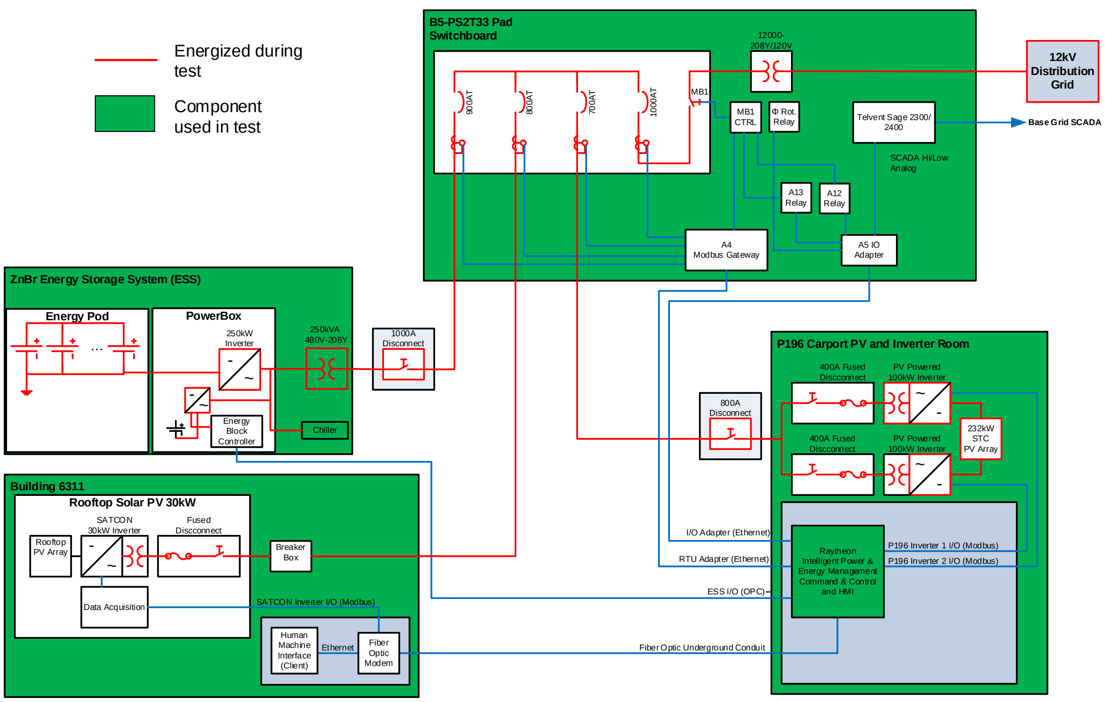


Figure 5-21: Test configuration for Islanded Mode Tests

5.4.4.1 Pre-Island Conditions Test

The purpose of Pre-Island Conditions Test is to demonstrate that the IPEM Controller and other monitoring and control equipment are functioning properly in order to assess the current state of the test setup. The IPEM Controller communicates with and pulls status from the various subsystems and provides that information to the user in order to make decisions about how to operate the microgrid.

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active and the Main Breaker is Closed.
3) The ESS is in Ready State.

Notional Test Procedure

1) Check/Set ESS System State to Ready State
2) Check ESS State of Charge
3) Check PV status on Inverters A, B
4) Check communications and status on Main Breaker

Results

This test was conducted on 10/24/15. The night before the ESS was brought to 0% SOC then charged to 100% overnight. The IPEM controller adequately checked the status of all of the various subsystems 1) ESS 2) PV Systems and 3) the Main Breaker

Item	Description of Desired Outcome	Outcome of Test
1	IPEM Controller acquires PV inverters, ESS and Main breaker status data. Data is made available to the system operator to assess islanding readiness	Complete

5.4.4.2 Island Transition Test

The purpose of the Island Transition Test is to test the behavior of the system when the Main Breaker is open and closed prior to conducting Full Islanded Testing.

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active and the Main Breaker is Closed.
3) The ESS is in Ready State.
4) Miramar Operations has been notified of the event.

Notional Test Procedure

1) Check/Set ESS System State to Ready State
2) Check ESS State of Charge
3) Check PV status on Inverters A, B
4) Check communications and status on Main Breaker
5) Open the Main Breaker
6) Check the status and comms of the Main Breaker
7) Check the status and comms of the ESS
8) Confirm the ESS has shut down and gone into standby mode.
9) Check status on PV Inverters A, B verify that they have de-energized
10) Close the Main Breaker
11) Check the status and comms of the Main Breaker
12) Check the status and comms of the ESS

13) Check status on PV Inverters A and B

Results

Item	Description of Desired Outcome	Outcome of Test
1	The IPEM Controller allows the Main Breaker to be opened and closed and acquires expected PV inverter, ESS and Main breaker status data.	Complete

This test was conducted on 10/24/15. The IPEM controller displayed the status of each of the subsystems and sensors of the microgrid. The test however did not use the HMI interface to open and close the Main Breaker, only to show status. The PV inverters were remotely via IPEM Modbus put in disable mode (as opposed to opening the AC disconnect) per AE's recommendations to NREL. The Satcon inverter was disabled manually by opening the AC and DC disconnects to the inverter. The Open/Close function for the Main Breaker was conducted from IPEM but through a manual process of changing the state through a terminal. The Main Breaker Opened as commanded and power was cut off to all systems. The UPS within the switchgear maintained power on the Main Breaker and IPEM equipment within the switchgear. The battery went into its back-up power mode. The PV inverters went offline and this was shown on the HMI. The Grid Status was reported to the HMI as Inactive, the ESS showed it was in Ready Mode, the sensors within the switchgear showed there wasn't any power on the feeder circuits. IPEM then sent a Close command to the Main Breaker remotely through a terminal interface and the Main Breaker closed, picking up the load of 6311. Power was returned back to 6311, the ESS and the PV inverters. The IPEM HMI showed the Grid Status change to Active and the power levels on each of the feeder circuits as well as the status on the PV inverters. It was noted from the HMI that one of the PV Inverters (Inverter B) did not establish comms after the normal 5 minute countdown. Once this was noted the inverter was visually inspected in the inverter room and it was noted that Inverter B's display did not show anything and there was no indication that the Inverter had powered up. A similar issue happened to Inverter A in July of 2014 during a planned outage and was attributed to failure of the auxiliary power supplies. Bob Butt at NREL had a Fluke Model 1735 Power analyzer connected to the building 6311 feeder circuit and recorded power quality from the system. The results of his recording are provided below.

> Worst case sag lasted 8 ms and was 109 V. Worst swell was 127 V and lasted 291 ms. Transient events would obviously be much faster but the test setup captured some short duration events, and none appeared to be very significant.
>
> Voltage THD was 2% in Phase A. It will be interesting to see how it changes with battery system connected.

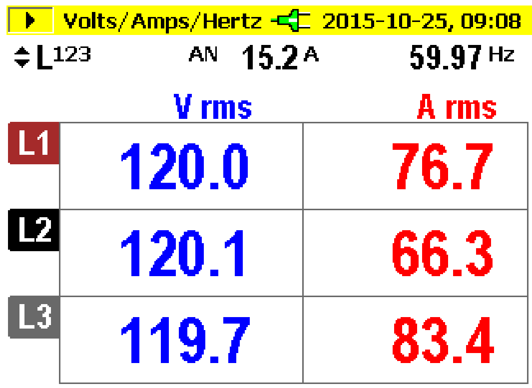


Figure 5-22: 3-Phase balance for voltage and current.

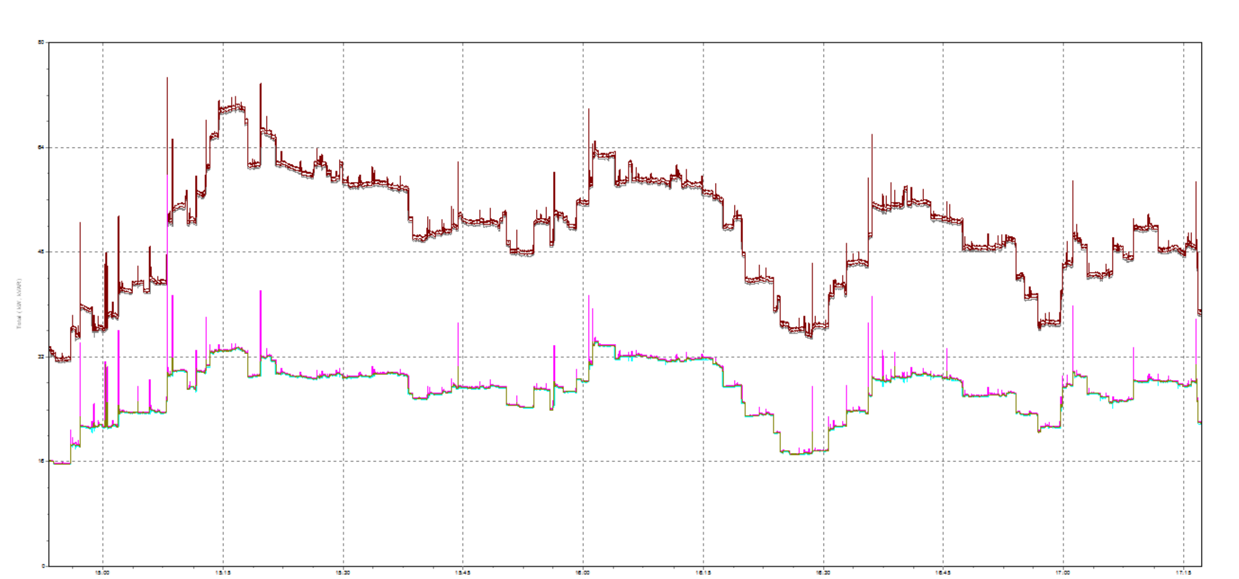


Figure 5-23: Plot of total real power (kW) and reactive power (kVAR) over time. Power factor ranged from about 0.86 to 0.89. Peak 6311 load on Sunday was about 70 kW at 1515.

During this and other tests, ground currents were observed at various grounding electrode connection points, as shown in Figure 5-24. The results of these measurements are shown in Table 5-5

Table 5-5: Results of ground current measurements.

Measurement Location	Date/Time	Amps, AC/DC	Notes
1	10/24 @1030	320 mA AC	
2	10/24 @1030	810 mA DC	
3	10/24 @1030	200 mA DC	

1	10/24 @1155	350 mA AC	Inverter, Energy Pod Aux. Power Only (chiller, heaters, controls)
2	10/24 @1155	820 mA DC	Aux. Power Only
3	10/24 @1155	380 mA DC	Aux. Power Only
1	10/25 @0915	250 mA AC	System Testing Underway, chiller running
2	10/25 @0915	170 mA, 700 mA DC	Testing Underway
3	10/25 @0915	275 mA DC	Testing Underway
4	10/25 @0915	265 mA AC	Testing Underway

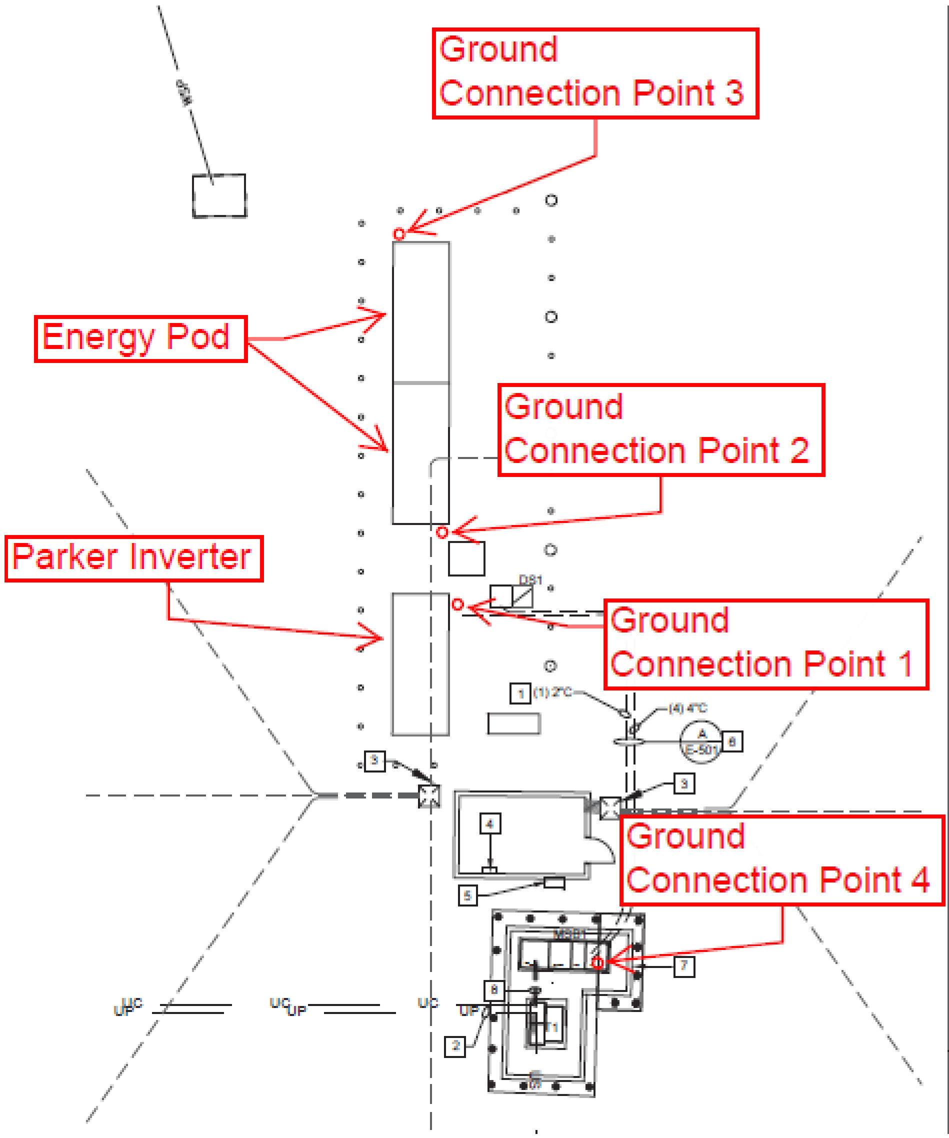


Figure 5-24: Ground current measurement schematic.

5.4.4.3 Islanded Operation with Battery Only Isolated from Circuit (Self Powered)

The Islanded Operation with Battery Only Isolated from Circuit (Self Powered) test is intended to go through the sequence of islanding with the battery isolated from the B5PS2T33 circuit. This is meant to exercise the sequence of commanding the battery to Islanding Mode from IPEM and allowing the battery to power up and provide power to its own overhead lead. Building 6311 will not lose power during this test. One of the AC interconnects to the battery will be Opened during this test to simulate a loss of power to the battery and prevent feeding power onto the B5PS2T33 circuit.

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active and the Main Breaker is Closed.

3) The ESS is in Ready State.
4) The ESS is charged to 100% SOC and remains higher than 90% prior to test
5) Outage approval has been granted by Miramar

Notional Test Procedure

1) Check/Set ESS System State to Ready State
2) Check ESS State of Charge
3) Check the status and comms of the Main Breaker
4) Check the status and comms of the ESS
5) Open one of the AC disconnect switches that feed into the Primus 208Y/480V transformer (TBR).
6) Verify that the battery has loss of power and goes into standby mode.
7) Set the ESS in Islanded Mode Manually through Primus EnergyBlock Controller Interface
8) Verify that the following sequence occurs
    a) The ESS restarts its power electronics in its stand alone setting and sends a message to the IPEM Controller that it is in islanding mode and provides the initial power to the load.
9) Monitor the load quality data being provided by the ESS through the IPEM HMI and power analyzers
10) Disable the ESS from being in Islanding Mode Manually through the EnergyBlock Controller Interface.
11) Verify that the following sequence occurs
    a) The EnergyBlock Controller commands the ESS to de-energize in Standby Mode causing power loss to the System.
12) Close the AC disconnect switches that feed into the Primus 208Y/480V transformer.
13) Verify that power is restored the Primus system and shows it's in its Ready Mode.
14) Repeat the previous steps as many times as required until sequence occurs smoothly then follow the sequence below.
15) Open one of the AC disconnect switches that feed into the Primus 208Y/480V transformer.
16) Verify that the battery has loss of power and goes into standby mode.
17) Set the ESS in Islanded Mode Manually through IPEM
18) Verify that the following sequence occurs
    a) The ESS restarts its power electronics in its stand alone setting and sends a message to the IPEM Controller that it is in islanding mode and provides the initial power to the load.
19) Monitor the load quality data being provided by the ESS through the IPEM HMI and power analyzers
20) Disable the ESS from being in Islanding Mode Manually through IPEM.
21) Verify that the following sequence occurs
    a) IPEM commands the ESS to de-energize in Standby Mode causing power loss to the System.
22) Close the AC disconnect switches that feed into the Primus 208Y/480V transformer (TBR).
23) Verify that power is restored the Primus system and shows its in its Ready Mode.

Results

Item	Description of Desired Outcome	Outcome of Test
1	The battery successfully transitions to Islanding Mode and provides the initial load to its overhead systems with no faults.	Complete
2	The battery successfully transitions to Grid Tied mode after Islanding test is complete.	Complete

This test was conducted multiple times throughout the weekend 10/23/15-10/25/15. The entry criteria was met and the battery side of the AC disconnect was opened at the SDG&E meter cabinet. This shut down power to the ESS. The battery would register the power outage and put the system in a Standby state reducing its overhead power while running on its UPS. The Primus EnergyBlock controller then commanded the ESS to go into Islanding mode triggering a series of events to power the EnergyCells to bring up the DC bus and then close the AC breaker on the Parker Inverter. Going through this process the first couple of times the team detected multiple sequences that needed to be re-coded as the flow of events required to go into islanding mode was better understood. One of the concerns going into this test was the phase rotation of the AC output of the Parker inverter during islanding mode. The phase rotation output of the Parker Inverter is hard coded into the system for its Islanded mode output. To determine if the battery was able to match the phase rotation of the 6311 load, it was noted that the ESS Chiller has the same phase rotation settings as 6311. If the ESS was able to pick up the load of the chiller then the settings for the phase rotation on the Parker inverter should be adequate for the 6311 load. When the ESS was brought up in Islanded mode the chiller it powered up successfully, therefore it is expected to adequately match the phase rotation required for 6311. For additional confirmation, the Ion 8600 meter at the main switchboard MSB1 displays phase rotation, and could be used to check utility and ESS phase rotation before B6311 is energized by the ESS. After this test was completed the ESS system was shut down and the system was deemed ready for Islanded Operation with Battery Only Test. It was also noted that during one of the controlled outages on 10/24/15 the AE inverters were disabled remotely via the Modbus interface then the AC power was interrupted. Upon return of power on of the AE inverters had a power supply failure and did not power back up. AE technical services was notified and repairs were scheduled however the AE Inverter B was not available during the tests leaving only one functional 100kW inverter for islanding testing.

This test was repeated on 10/25/15 after attempting the Islanded Operation with Battery Only Test to allow Primus the ability to determine the cause of why the EnergyCells MOSFETs were being damaged and to iron out the sequencing for the ESS to be brought up and successfully brought out of Islanding Mode.

After conducting the Islanded Operation with Battery Only test on 10/25/15 there were a couple sequencing issues that needed to be investigated to avoid further damaging more EnergyCells in the ESS. At this time Islanded Operation with Battery Only Isolated from Circuit (Self Powered) was then revisited to understand the proper sequence of shutting down the ESS to avoid damaging the EnergyCells. The weekend concluded with still running the Islanded Operation with Battery Only Isolated from Circuit (Self Powered) test. During the tests the team was going through iterations of the ESS code to reduce the voltage stress on the EnergyCells in a controlled manner. Without this sequence working properly the EnergyCells were damaging the MOSFETs in their power electronics which requires removal of the EnergyCell to repair. Therefore the Primus team was prioritized to concentrate on this issue so as to avoid damaging any further EnergyCells. The ESS needs at least 7 EnergyCells to provide adequate DC voltage and current for the load. At the start of the weekend there were 13 out of 14 EnergyCells functioning. During the Islanded Operation with Battery Only testing 3 more of the EnergyCells failed due to damaged MOSFETs. After going back to conducting Islanded Operation with Battery Only Isolated from Circuit (Self Powered) a couple more EnergyCells failed in the afternoon dropping the system to below 5 EnergyCells. It was at this time the Islanding demo was concluded to allow Primus to finish their assessment of the proper shutdown sequence and repair the damaged MOSFETs within the faulted EnergyCells.

5.4.4.4 Islanded Operation with Battery Only

The Island with Battery only test is intended to go through the sequence of islanding prior to establish a performance baseline prior introducing the PV generation into the microgrid. The PV will be manually disabled for this test.

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active and the Main Breaker is Closed.
3) The ESS is in Ready State.
4) The ESS is charged to 100% SOC and remains higher than 90% prior to test
5) Outage approval has been granted by Miramar

Notional Test Procedure

1) Check/Set ESS System State to Ready State
2) Check ESS State of Charge
3) Check PV status on Inverters A, B
4) Manually de-energize the PV inverters by disabling them through their communications interface (e.g. Modbus).
5) Check PV status on Inverters A and B and verify they are offline
6) Check the status and comms of the Main Breaker
7) Check the status and comms of the ESS
8) Enter Islanded Mode Manually through IPEM HMI
9) Verify that the following sequence occurs
    a) The Main Breaker is opened and the utility power to BS5PS2T3 is disrupted.
    b) Upon loss of power the System transitions into Islanding Mode. During the transition to Islanding Mode the following steps occur:
        i) ESS de-energizes and goes into back-up power mode but still is in its grid connected setting and waits for the islanding command from the IPEM controller.
        ii) The IPEM Controller and HMI stay on-line powered by its UPS. The HMI displays that the Grid is down, reports the loss of comms with the Inverters as it transitions into Islanding Mode.
        iii) The IPEM Controller commands the ESS to enter Islanding Mode. The ESS restarts its power electronics in its stand alone setting and sends a message to the IPEM Controller that it is in islanding mode and provides the initial power to the load.
10) Monitor the load quality data being provided by the ESS through the IPEM HMI and power analyzers
11) Disable Islanding Mode Manually through the IPEM HMI
12) Verify that the following sequence occurs
    a) The IPEM Controller commands the ESS to de-energize in Standby Mode causing power loss to the System. The IPEM Controller and ESS operate off of back-up power and the System goes into Grid Transition Mode.
    b) The IPEM Controller commands the Main Breaker to close returning grid power to the System.
    c) The IPEM Controller commands the ESS to return to its grid connected setting.
    d) The System is now in Ready Mode.

Success Criteria

Item	Description of Desired Outcome	Outcome of Test
1	PV inverter faults are identified and displayed to the system user via the IPEM HMI	Complete
2	The system maintains voltage, frequency, phase-balance and harmonics within a pre-determined range while PV inverters are faulted and brought off line	Complete
3	The PV inverters can be brought back on-line and resume operation in accordance with the pre-determined PV curtailment levels	Complete

This test was conducted in the afternoon (~15:15) on 10/24/15. The PV inverters were disable remotely via IPEM. The Phase Rotation on 6311 was inspected on the ION 8600 smart meters to start. They read: Phase A – 0.0, Phase B -120, Phase C 119. At approximately 15:57 the Main Breaker was opened via the MOXA IO device. Power was interrupted to B5PS2T3 switchgear. The IPEM controller, ESS, and switchgear all stayed on on their appropriate UPSs. The team used the Primus EnergyBlock controller to bring the battery up in Islanding mode. During the startup process the ESS faulted and it appeared some EnergyCells reported faults as well. The test was aborted at this time and IPEM reclosed the Main Breaker returning power back to the system. A plot of the outage is shown in Figure 5-25 below. Upon further inspection it was determined that fault in the EnergyCells was due to damaging the MOSFETs during the test. This was suspected to be caused by the shutdown sequence of the ESS when exiting Islanding Mode. At the end of the test the team needed time to analyze the shutdown sequence and software code with their software engineers. The day was concluded until one of Primus' Software Engineers flew in the morning on Sunday 10/25/15 and could review the software code and sequencing.

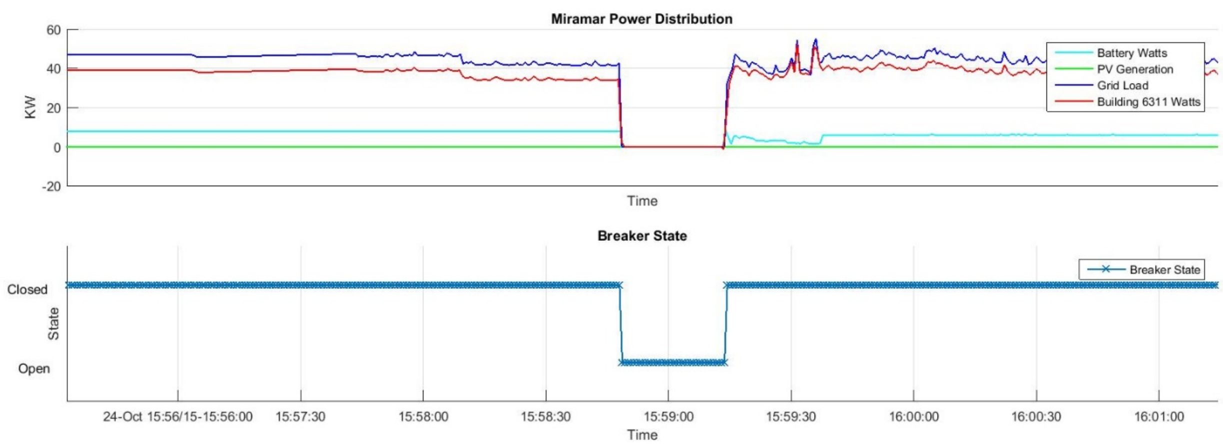


Figure 5-25: Timeline for Islanded Operation with Battery Only test on 10/25/15.

This test was repeated on the morning of 12/12/15 after Primus Power was able to validate the proper sequencing for the shutdown of EnergyCells when exiting Islanding Mode. Once validated another islanding demonstration test was scheduled for 12/11/15 to 12/13/15. On 12/10/15 a component failure occurred in one of the H-Bridges of one of the EnergyCells activated a smoke detector within the EnergyPod. The audible alarms were triggered and MCAS personnel heard

the alarm and notified the Miramar Fire Department. The event did not result in a fire however the event signifies the importance of having proper safety monitoring and fire protection mechanisms in place. Due to the damaged H-Bridge the EnergyCell with that component as well as an adjacent EnergyCell would not be available during the 12/11-12/13 islanding tests. Therefore the system would only have 12 of the 14 EnergyCells available for testing.

Figure 5-26: Photo of damaged H-bridge system.

On the morning of 12/12/15 the Islanded Operation with Battery Only Test was repeated and the system successfully islanded at 9:31AM. The microgrid was commanded via the IPEM controller to enter islanding model. The Main Breaker was opened at 9:27AM and Building 6311 lost power. The IPEM controller commanded the battery to start up in islanding mode and at 9:31AM the ESS picked up the loads for 6311 (Figure 5-27 and Figure 5-28).

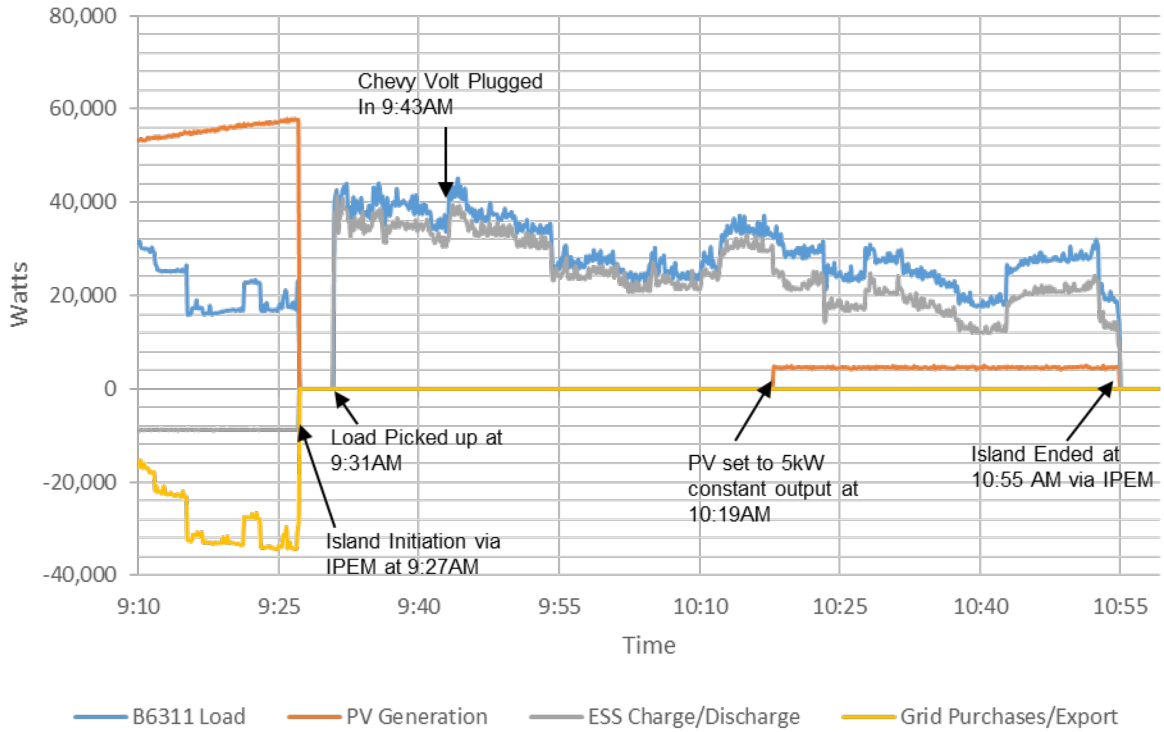


Figure 5-27: Summary of islanding data on the morning of 12/12/2015.

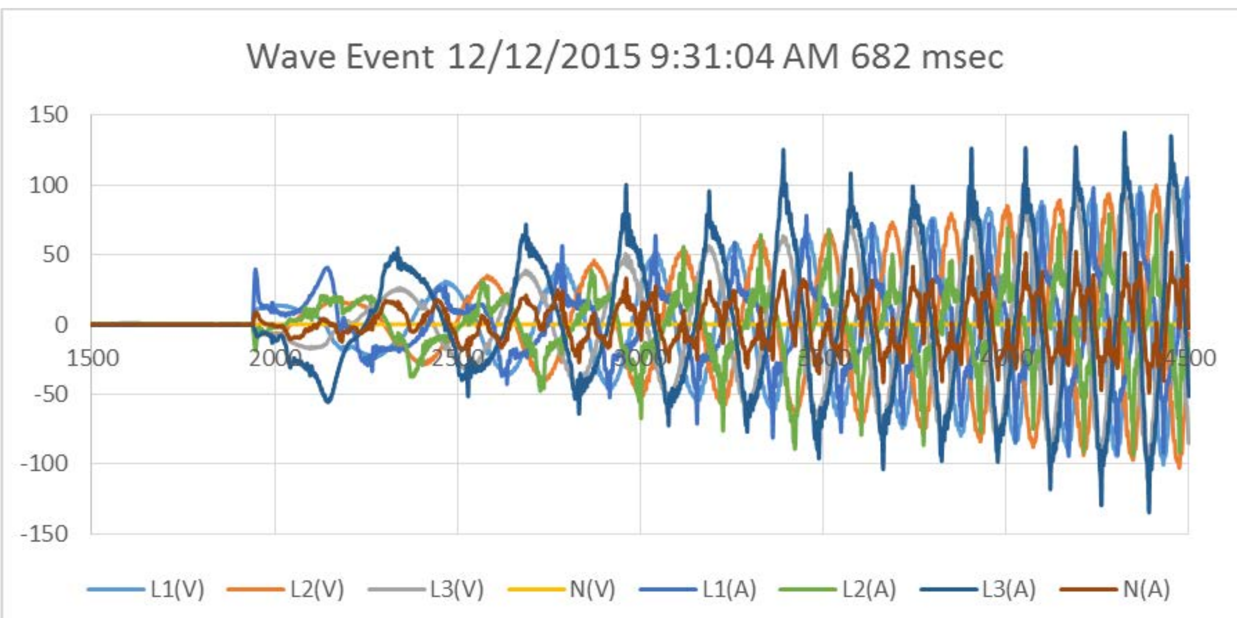


Figure 5-28: Voltage and current waveform of building 6311's load provided by the ESS.

The system was allowed to run to verify stability in the ESS' ability to manage the load on the building. The ESS was monitored and showed it was regulating the voltage within normal operating parameters (Figure 5-29).

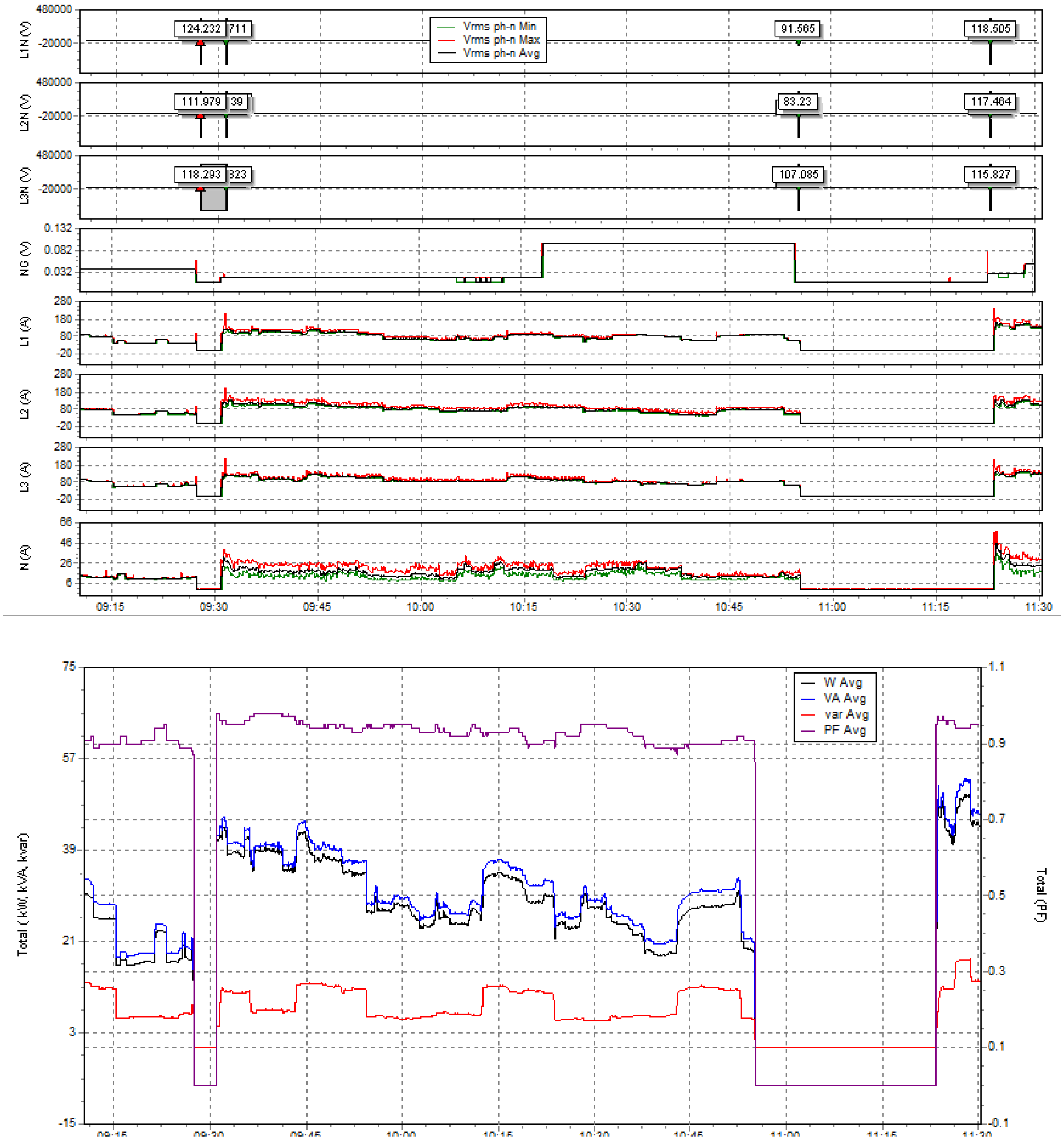


Figure 5-29: Detailed load data taken from Fluke 437II that was attached to Building 6311 circuit during 12/12/15 morning islanding test.

Once everything was determined to be stable, at 9:43 AM a Chevy Volt was plugged into the circuit to add a large battery load to the building to see if the ESS could handle the type of load.

Figure 5-30: Photo of Chevy Volt used in islanding demonstration outside of building 6311.

At 10:17AM one of the AE inverters was turned on to provide 5kW of constant power output to check the ESS response to other inverter generation sources (Figure 5-31).

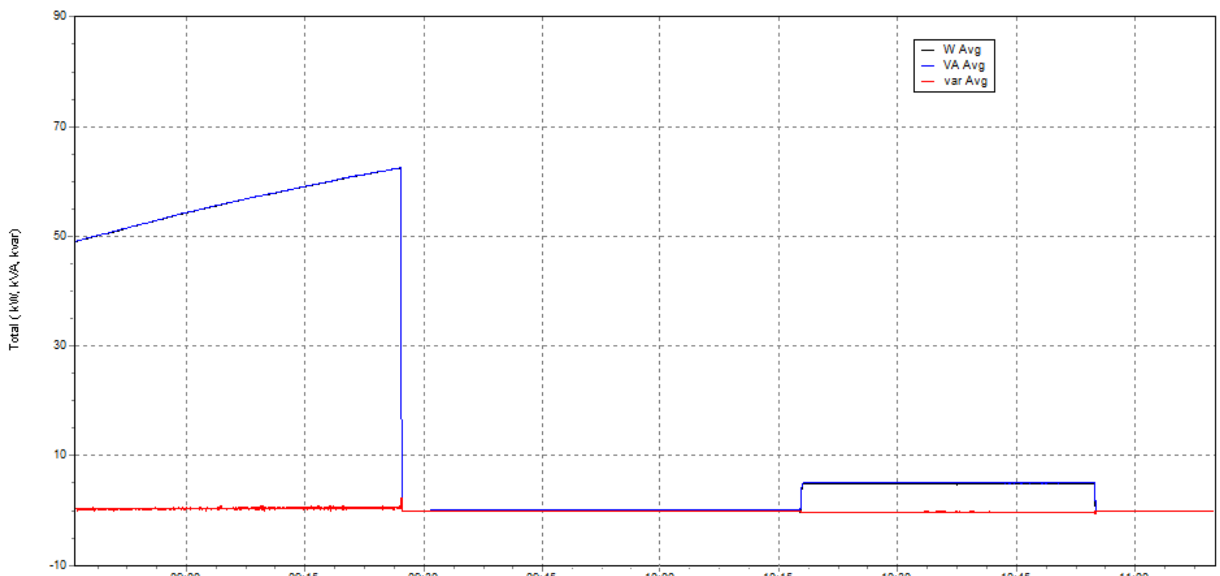
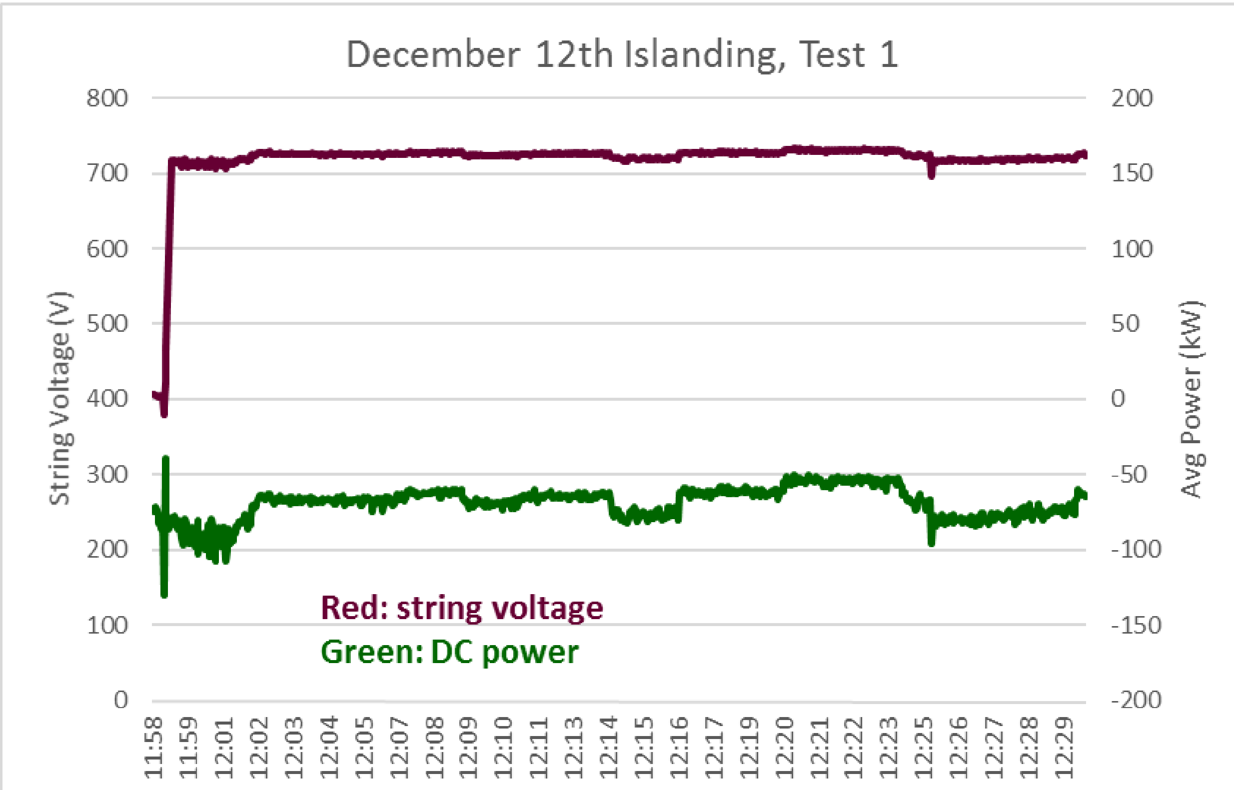


Figure 5-31: Data from Fluke 1735 meter that was attached to the P196 PV circuit.

For the morning microgrid the system ran until 10:55AM. At this time the team wanted to make sure all of the safety interlocks were functioning that prevent the microgrid from reconnecting to the grid with the ESS still in voltage control mode which could cause catastrophic failure. Within the IPEM controller subsystem there are both electrical relays and software logic that prevent this from happening. The team took the time to monitor all of the software code and subsystem status to make sure the proper logic was followed for a reconnect. As an extra precaution the team had the 12kV feeder breaker to the B5PS2T3 switchgear opened. The team then exited islanding mode and attempted a re-connect with the 12kV feed de-energized. There is a phase rotation relay at

B5PS2T3 main breaker that determines if the Miramar distribution system is energized and in phase. The IPEM controller will not allow the Main Breaker to close when attempting to exit islanding mode if Grid is not present on the primary side of the Main Breaker. Because the 12kV feed on the primary side was de-energized the IPEM controller should recognize this and prevent the Main Breaker form closing. During the attempted re-connect the IPEM controller properly de-energized the battery and the phase rotation relay prevented the Main Breaker from closing showing that the safety interlocks were functioning properly. At this time the team closed the 12kV feeder breaker, re-energizing the primary side of the B5PS2T3 switchgear. At 11:23AM the IPEM controller closed the Main Breaker and grid power was restored to Building 6311.



5.4.4.5 **Intentional Island with PV Tests**

The Intentional Island with PV Test exercises the Islanding Scenario with the PV system available as a DR along with the ESS using load from Building 6311 un-altered. The purpose of the test is to conduct an end to end island scenario to characterize the behavior of the system using the ESS and PV to meet load demands while isolated from the Miramar Utility Grid. The PV system will be curtailed at various PV penetration/power ratio levels to determine what levels of PV penetration generate instability of the distributed generation outside of a pre-determined range of conditions. Power quality will be characterized as a function of load power factor and in the presence of load transients. Component (e.g., inverter) level faults will be introduced into the system to verify the system's ability to identify and recover from component fault conditions.

Prerequisites

1) The IPEM controller software is up to date and the HMI is running.
2) The Miramar utility grid is active and the Main Breaker is Closed.

3) The ESS is in Ready State.
4) The ESS is charged to 100% SOC and remains higher than 90% prior to test
5) Outage approval has been granted by Miramar

Notional Test Procedure

1) Check/Set ESS System State to Ready State
2) Check that the ESS State of Charge is > 90%
3) Check PV status on Inverters A, B
4) Check communications and status on Main Breaker, the Main Breaker should be closed and the communications status green
5) Enter Islanded Mode Manually through IPEM HMI
6) Verify that the following sequence occurs
    a) The Main Breaker Opens and reports this status to the HMI
    b) The utility power to Building 6311 is disrupted
    c) Upon loss of power the system transitions into Islanding Mode. During the transition to Islanding Mode the following steps occur:
        i) ESS de-energizes and goes into back-up power mode but still is in its grid connected setting and waits for the islanding command from the IPEM controller.
        ii) The PV Inverters A & B de-energize due to loss of grid presence.
        iii) The IPEM Controller and HMI stay on-line powered by its UPS. The HMI displays that the Grid is down, reports the loss of comms with the Inverters as it transitions into Islanding Mode.
        iv) The IPEM Controller directs the ESS to enter Islanding Mode. The ESS restarts its power electronics in its standalone setting and sends a message to the IPEM Controller that it is in Islanding Mode, and provides the initial power to the load. The Islanding clock starts.
        v) The IPEM Controller calculates what the load of the system is within the first 5 minutes and sets the initial curtailment set point for the PV Inverters below 50% of the load. As the load changes the IPEM subsystem changes the curtailment set point of the PV Inverters to remain 50% below the required load amount.
7) Monitor the load quality data being provided by the ESS and PV through the IPEM HMI and power analyzers.
8) Repeat previous steps increasing the PV penetration in 5% increments. At each increment assess power quality provided to the load for compliance with IEEE1547.4
9) Determine which PV penetration level the power quality to the load exceeds the requirements in IEEE1547.4**Error! Reference source not found.**
10) Disable Islanding Mode Manually through the IPEM HMI
11) Verify that the following sequence occurs
    a) The IPEM Subsystem commands the PV inverters to disable.
    b) The IPEM Subsystem commands the ESS to de-energize in Standby Mode causing power loss to the System. The IPEM subsystem and ESS operate off of back-up power and the System goes into starts its transition into Grid Tied Mode.
    c) The IPEM Subsystem commands the Main Breaker to close returning grid power to the System.
    d) The IPEM Subsystem commands the PV Inverters to enable and sets the curtailment to 100%.
    e) The IPEM Subsystem commands the ESS to return to its grid connected setting.
    f) The System is now in Grid Tied Mode.

Results

Item	Description of Desired Outcome	Outcome of Test

1	The system successfully transitions from grid-connected to islanded mode via direction provided through the IPEM HMI	Complete
2	The system maintains phase balance, voltage, frequency and harmonics within pre-determined limits for all, or a subset of tested PV penetration levels	Complete
3	The system successfully transitions from islanded mode to grid-connected mode via direction through the IPEM HMI	Complete

This test was conducted on the afternoon of 12/12/2015 and through the day on 12/13/2015. On the afternoon of 12/12/2015 after the successful completion of the Islanded Operation with Battery Only Test in the morning the system was then tested with increased amounts of PV to further check the microgrids ability to function with shared inverter based generation sources. For this test to simulate a Grid power loss the 12kV feed to the B5PS2T3 was opened, causing power loss to Building 6311. The 12kV feed was opened at 3:19PM. This was detected and shown on the IPEM HMI. The system was put into Islanding mode via the IPEM controller. The ESS was enabled and picked up the loads at 3:25PM0 (Figure 5-32).

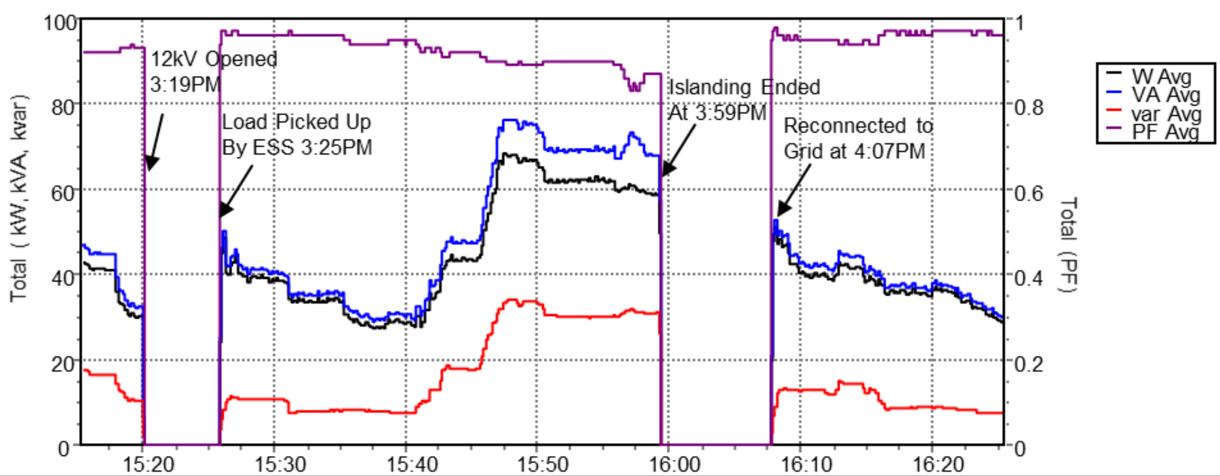


Figure 5-32: Power data from the Fluke 437 that was attached to building 6311 circuit during 12/12/15 afternoon islanding.

At about 3:36 one of the AE inverters was enabled and manually curtailed through the AE inverter Modbus interface at 5kW output. The auto-curtailment feature within IPEM was being updated within and was not available for this test so manual curtailment set points were used through the Modbus interface on the AE inverter. At 3:44 the curtailment was set to 10kW output, then 15kW, and then ultimately curtailed at 20kW. Due to sun beginning wane over the horizon PV was maxed out at ~19kW and slowly started to decrease as the sun continued to set dropping to 17kW. At this time the team wanted to observe a sudden drop out of PV generation and see the response of the ESS so the AE inverter was disabled at ~3:50PM. The ESS responded generate more current as it considered it an increase in load. At 3:56 the AE inverter was re-enabled at the 20kW curtailment setting and the maximum output it could generate was ~14kW. The profile for the PV generation is shown in Figure 5-33 below.

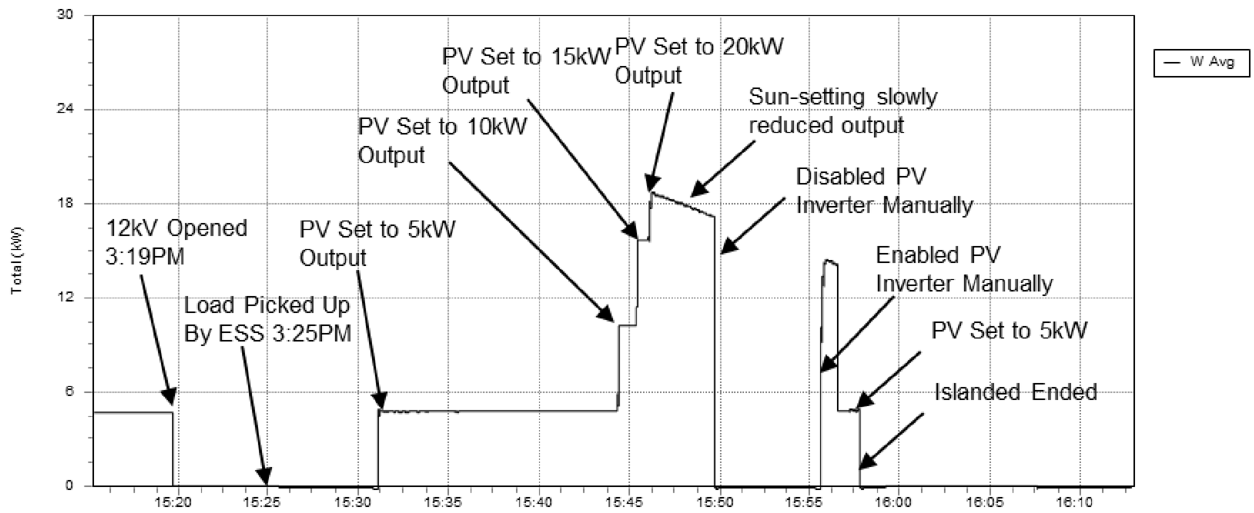


Figure 5-33: Power data from the Fluke 1735 meter that was attached to the P196 PV circuit during 12/12/15 afternoon islanding.

As the AE inverter energized one of the EnergyCells was starting to lose voltage and took itself out of current source. This in addition to interaction with the AE inverter started causing oscillations in the voltage control of the microgrid. Small flickers were observed in the lights within the building. The AC waveform during this time was recorded on the Fluke 437 and is shown in Figure 5-34.

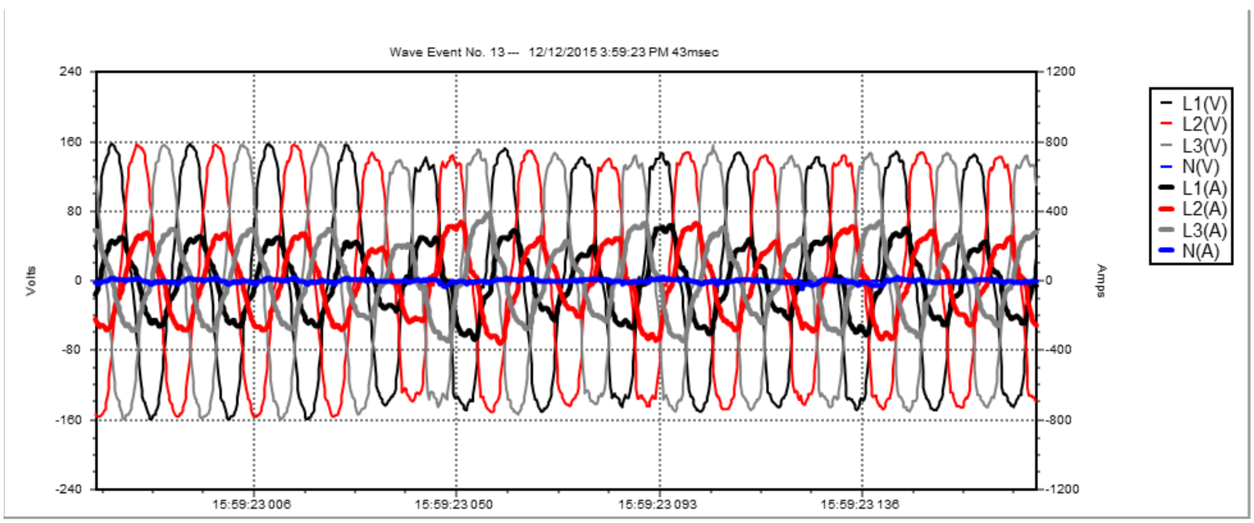


Figure 5-34: The AC waveform collected from the Fluke 437 during the final seconds of islanding the system.

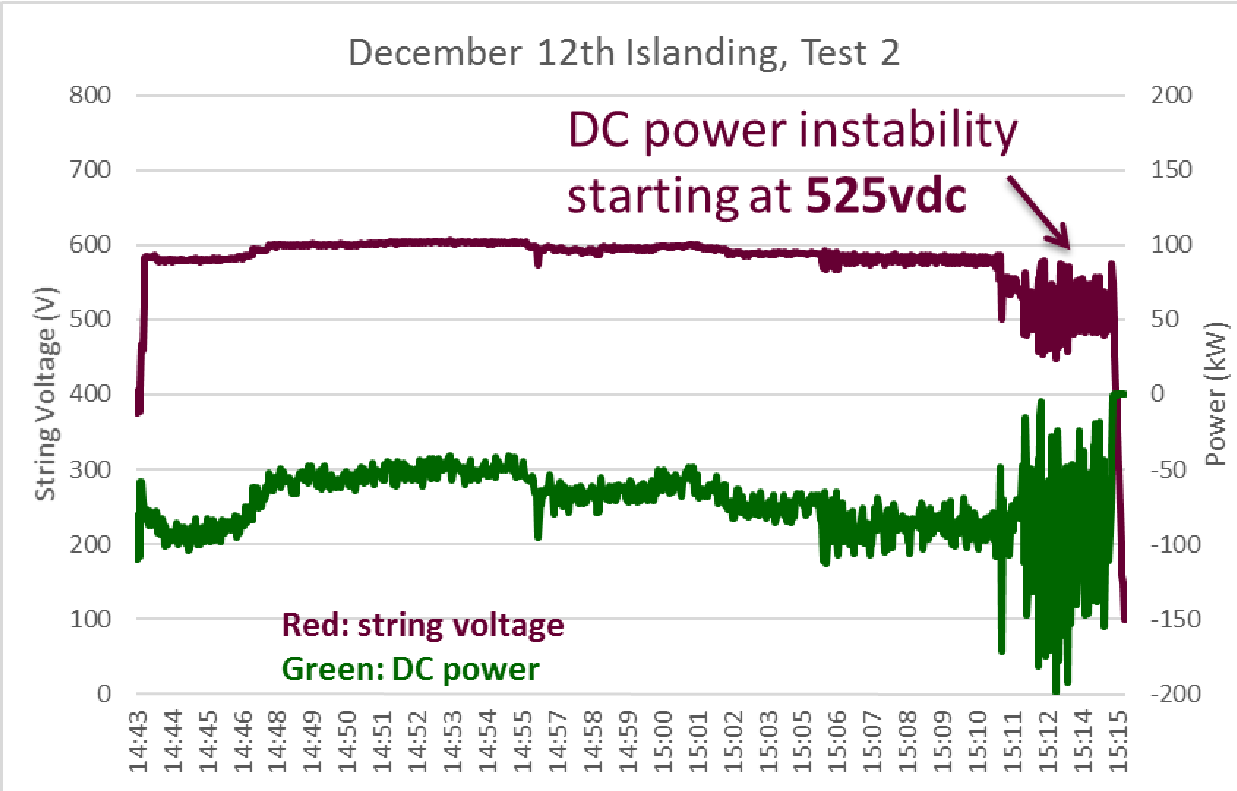


Figure 5-35:

At this point the team decided to that it had enough data on the system interactions and decided to end the islanding test. The team then gathered the data and made updates to the control logic of the system for another round of islanding tests the next day. The IPEM controller disabled the ESS and the Miramar operations crew closed the 12kV feed to the B5PS2T3 primary side. The IPEM controller then closed the Main Breaker and power was restored to 6311.

On 12/1315 this test was repeated with the expectation of including the auto-curtailment functionality from the IPEM controller to island the system and determine the maximum PV penetration level achievable while still maintaining stability of the system. The ESS was charged overnight starting at 3:00AM until ~8:00AM (Figure 5-36). The starting conditions for this test were 12 out of 14 EnergyCells were fully functional in the ESS, one 100kW AE inverter was fully functional, and full functionality of the IPEM controller.

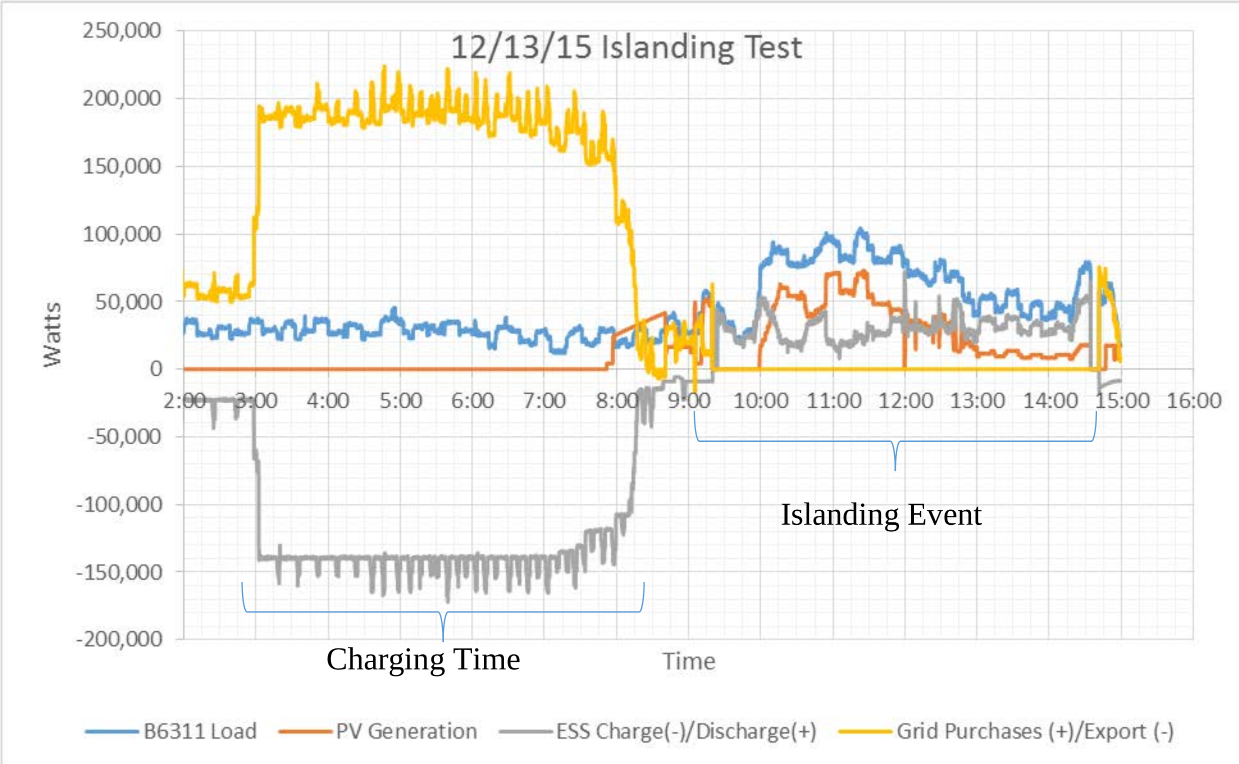


Figure 5-36:

At 9:19AM the 12kV feed to B5PS2T3 was opened shutting off power to building 6311. The system was commanded to enter Islanding Mode via the IPEM HMI. The IPEM controller commanded the ESS to boot up in Islanding Mode and after about 4 minutes the ESS picked up the load on the building. Once the load was picked up the functioning AE inverter detected a firm grid presence and started its boot up and 5 minute countdown to energize per its UL1741 requirements. At this time the team really wanted to determine the maximum PV penetration that the system could achieve while in a real islanding situation. The ESS needs to provide a minimum level of current in order for its current voltage control logic to remain stable. The minimum required current equated to the battery needed to constantly output a minimum of 10kW of power. The Primus team wanted to keep a comfortable margin so they suggested maintaining 20kW of minimum power output of the battery. The team was targeting to get higher than 75% PV penetration. Because of the battery needing to output a minimum of 20 kW the load on the building needed to be at least 80kW, as shown in Figure 5-37.

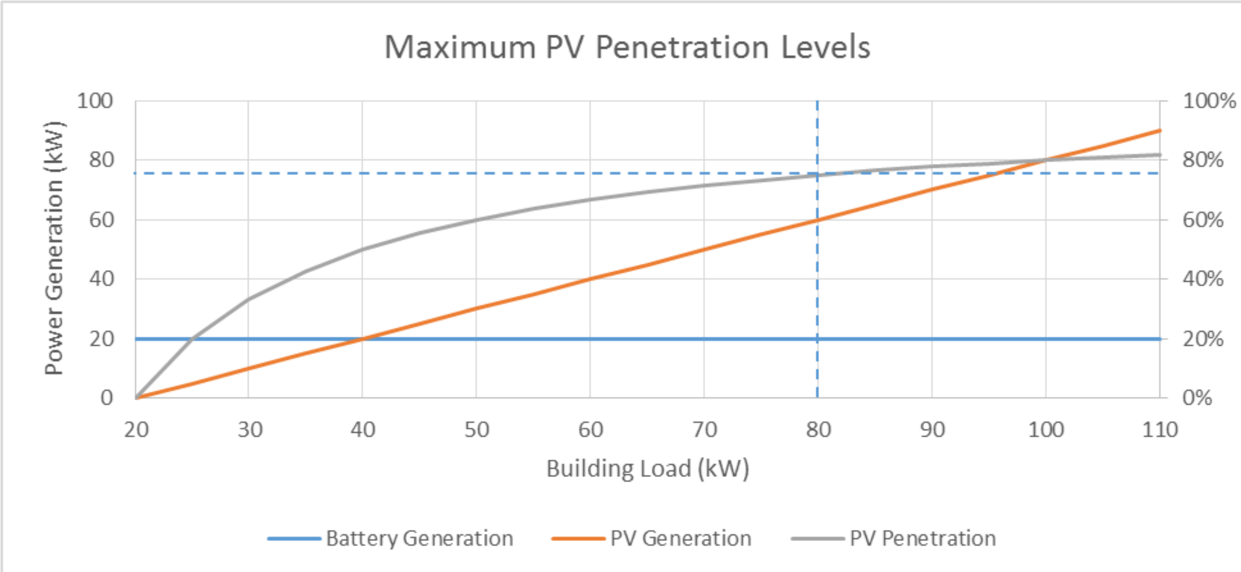


Figure 5-37: Graph showing the theoretical relationship of building load, PV generation, and minimum battery generation output and how it relates to PV penetration levels.

When the Islanding test started the building load was running about between 30-50kW. The team needed to get the load on the building higher so the team increased the load by turning on all of the AC systems, various space heaters, plugging in the Chevy Volt, and turning on all of the computers in the building. As the load started to increase around 9:54AM the AE PV inverter was enabled with using the auto-curtailment function (Figure 5-38).

Figure 5-38: Screenshots of the IPEM HMI during the 12/13/15 islanding event. Screenshot shows the initial loads of building 6311, ESS status and PV generation status. There is currently no PV output but the status on Carport A inverter (shown in red square) indicates the inverter is online and in its Startup/Bootup delay per UL1741 in the left image and in its Idle mode ready to output power in the right image.

The auto-curtailment function automatically changes the output power of the PV system to stay under a maximum PV penetration value. As the load increases the IPEM controller increases or decreases the PV power output to stay within the set PV penetration limit. The PV inverter was initially enabled at 30% PV penetration at 9:59AM and was steadily increased by 5% increments

until 10:32AM when the PV penetration was set to 75%. The PV penetration was then ramped down at 5% increments until 10:37AM when it reached 50% and was left for 26 minutes (Figure 5-39).

Figure 5-39: Screenshots of the IPEM HMI during the 12/13/15 islanding event. These screenshots show the initial output power of the PV system and its relationship with the load and the ESS output power. The image on the top is at 9:59AM when the PV penetration level was initial set at 30%. The image on the right is at 10:34AM when the PV penetration level was set at 65%.

At 10:53 AM the PV penetration level was increased from 50% to 70% and then steadily increased to 80% (Figure 5-40).

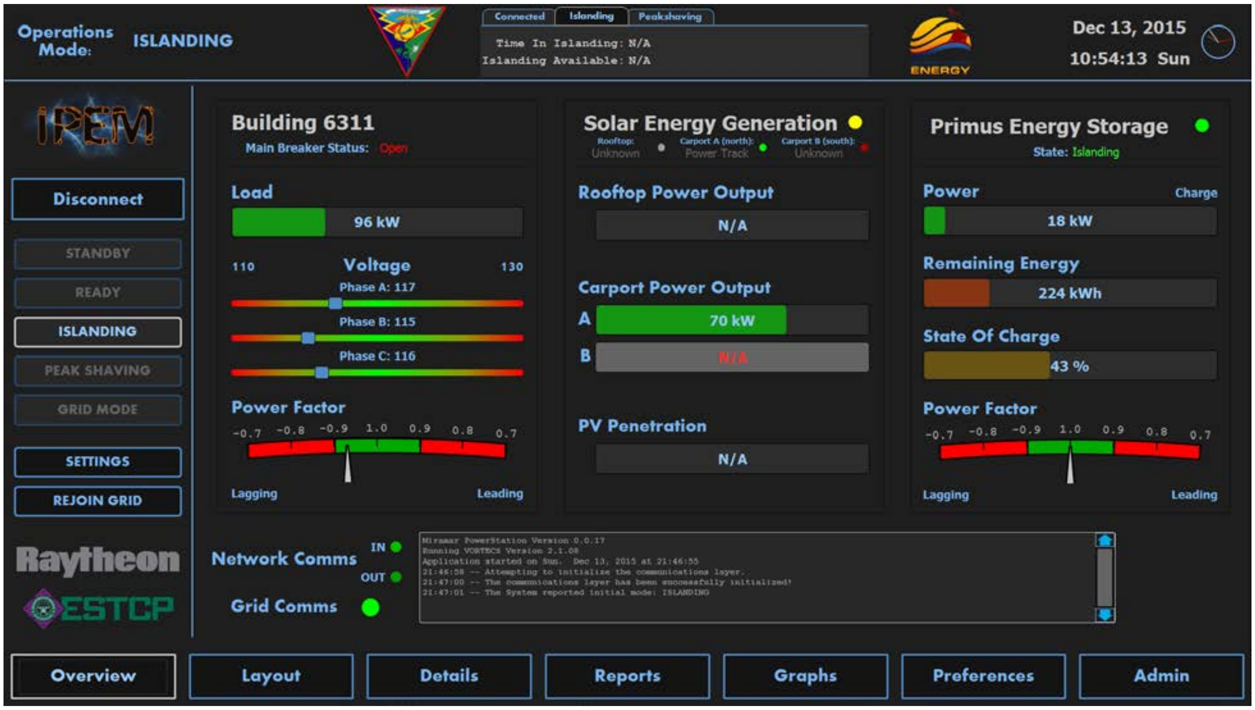
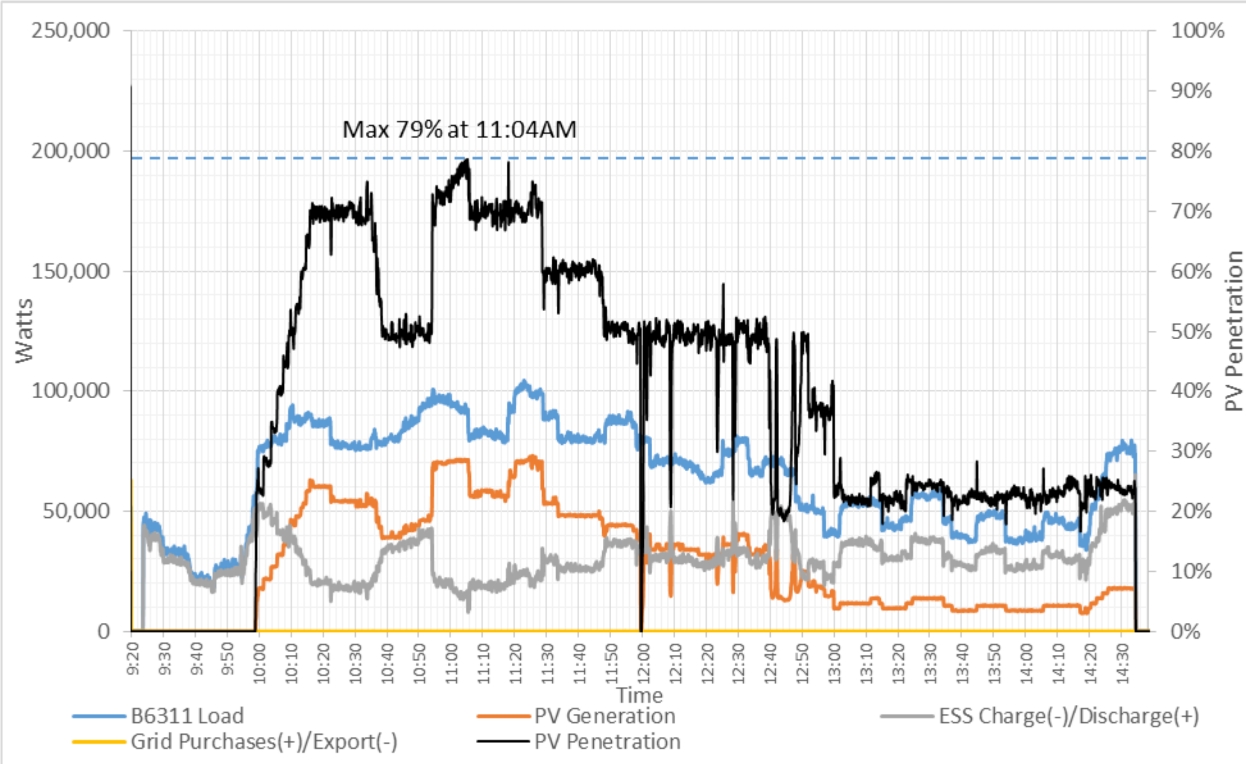


Figure 5-40:

At the 80% setting the PV system was maxed out due to the available sunlight during the day. At this point the maximum PV penetration level was achieved at 11:04AM at 79%. At 11:30AM the PV penetration was set back to 60% and then back to 50% at 11:50AM.



Just before noon clouds started appearing on the horizon heading towards Miramar (Figure 5-41). At ~12:00PM larger clouds started passing over the carport PV system causing the PV generation to drop very quickly.

Figure 5-41: Clouds forming in the southwestern sky.

As the PV generation dropped the ESS responded to control the voltage by provided more output power to meet the load. This occurred multiple times through the day. A complete summary of the load profile, PV generation, ESS charge/discharge for the islanding event is shown in Figure 5-42 below. The largest cloud transient occurred at 11:58:43 and the PV output went from 43kW down to 0kW in two seconds (21.5 kW/s).

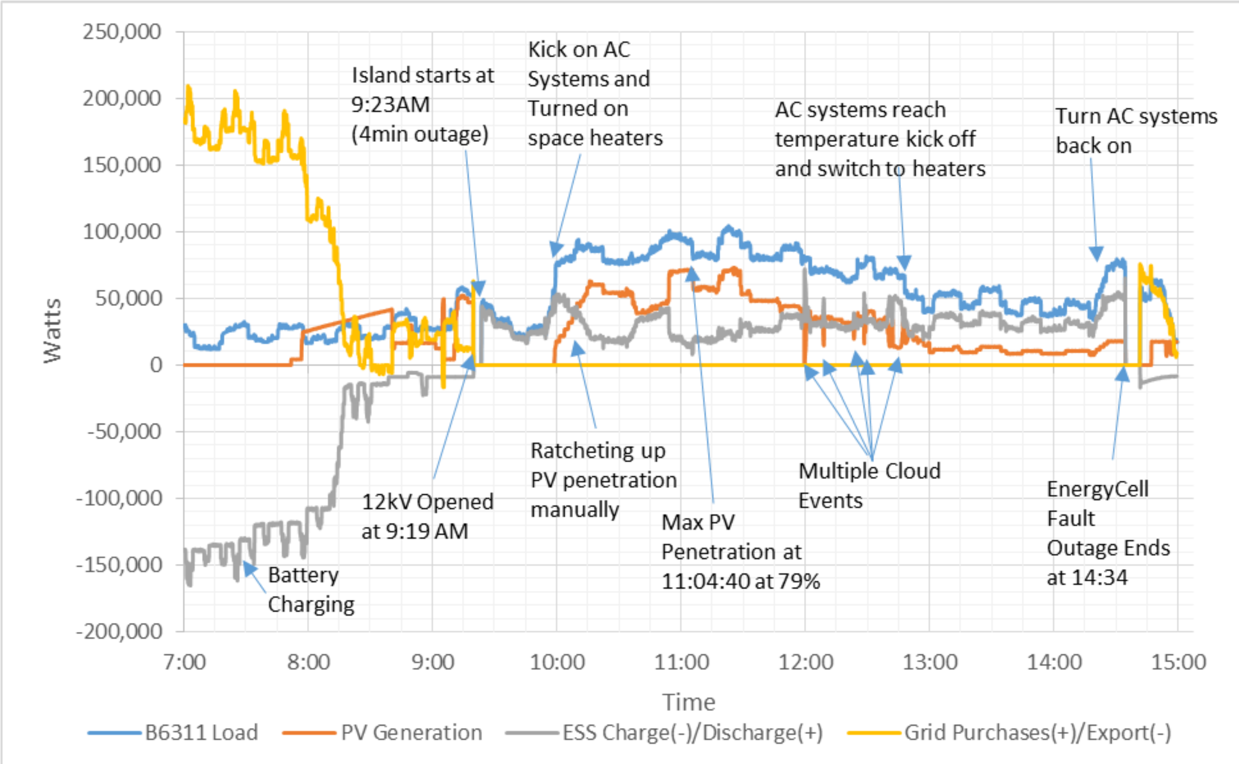


Figure 5-42: Summary load and generation profile during 12/13/15 islanding demonstration test.

At 2:34PM the ESS reported a fault which caused its central regulator to ramp itself down and go into its inactive mode. The building lost power and the IPEM controller reported the ESS in its Inactive state (Figure 5-43).

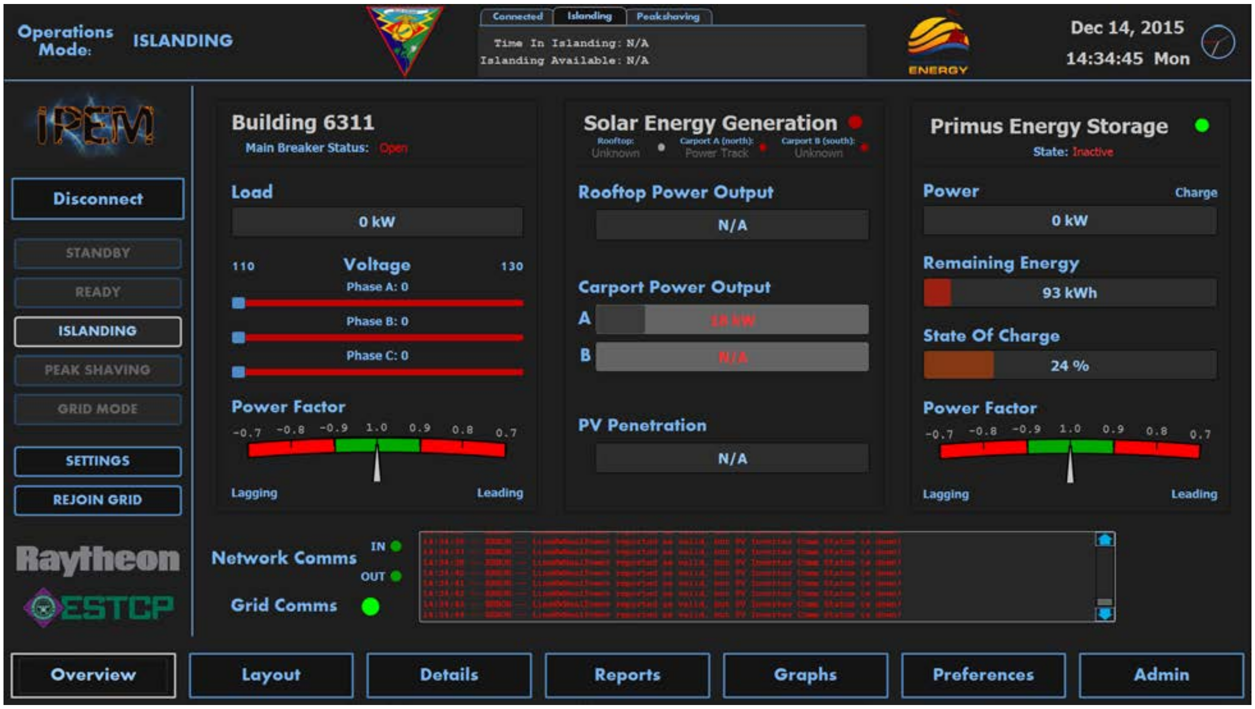


Figure 5-43: Screenshot of IPEM HMI at taken 2:34 when the ESS exhibited a fault and went into its inactive mode.

At this point the 12kV breaker to the B5PS2T3 circuit was closed re-energizing the primary side. The system was commanded to exit Islanding mode and reconnect to the grid via the IPEM HMI. The Main Breaker was then closed and power was restored to the building. This concluded the final islanding test of the system. Data was collected from all metering devices and the system was set back into Standby mode. The system successfully islanded under multiple load conditions for 5 hours and 10 minutes.

5.5 SAMPLING PROTOCOL

The sampling protocol during the various operational tests and demonstration are described below.

Data Description

- Sample Rate = (1-5 second intervals for IPEM controller, subsecond intervals for power analyzers)
- Grid input
- PV input
- Building load and quality (PF, CF)
- ESS power level and direction (charges vs discharge)
- Data transmission (to and from IPEM, ESS, PV Inverter)
- Response time

Data Collector(s)

- Raytheon Personnel

Data Recording.

- Automated:
- The IPEM control unit will log all variables in its internal database
- Calibrated Power measurement equipment will be use to validate the IPEM data

Data Storage and Backup

- IPEM controller employs built in flash memory which will store all collected data
- Remote monitoring data storage unit

Data Collection Diagram:

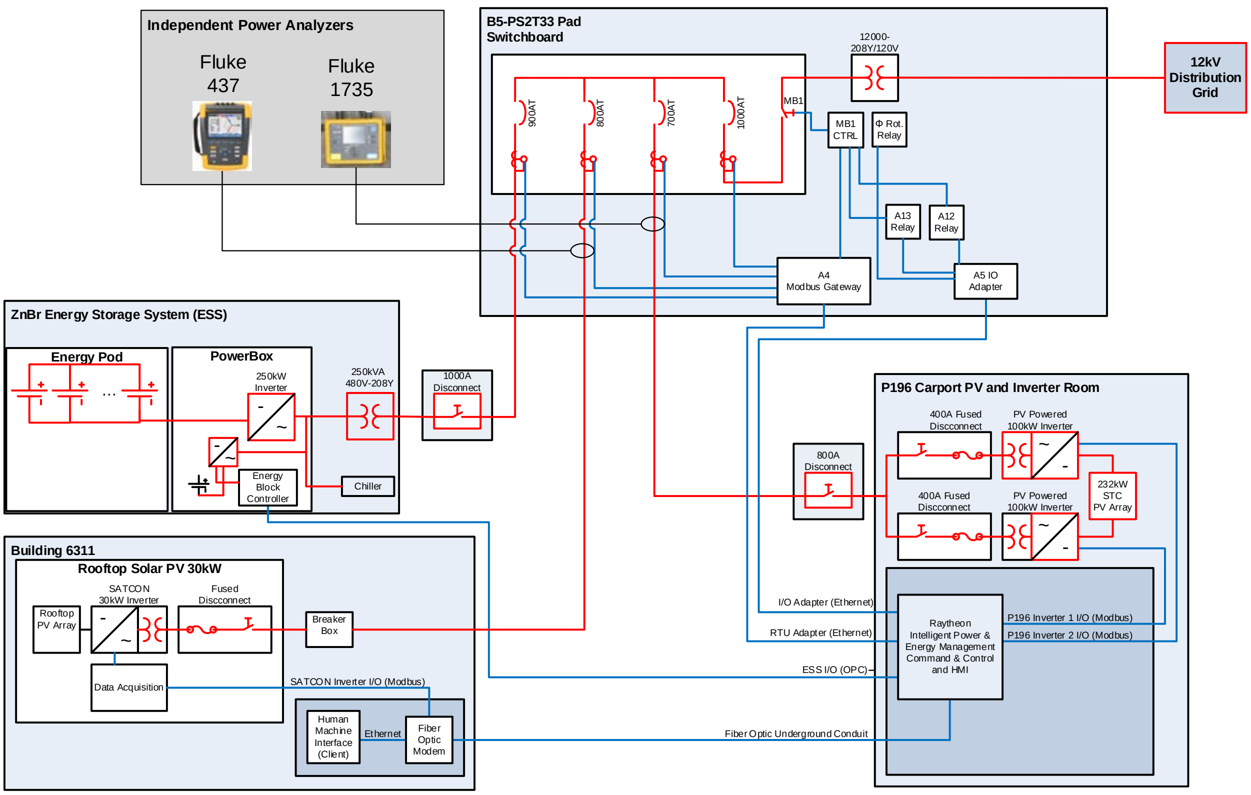


Figure 5-44: Detailed schematic of the interconnection of the various subsystem components of the installation.

5.6 SAMPLING RESULTS

Provide a detailed summary of all sampling results in terms of both temporal and spatial dependence as appropriate. Liberal use of graphics and tables is encouraged. The Final Report serves as the archived document for all data gathered during the demonstration. All results should be reported in this section or summarized and provided in detail in appendices.

6 PERFORMANCE ASSESSMENT

6.1 ISLANDING DURATION

The success criteria for this performance objective was that building loads would be met by the ESS and PV for at least 72hrs under controlled load conditions meeting power quality standards of IEE1547.4.

During the final demonstration tests on 12/13/15 the system was able to successfully island for 5 hours and 10 minutes. This was assessed by calculating the time period that the building 6311 was picked up by the ESS and when the load couldn't be sustained anymore and the building lost power. The data was also analyzed to determine if the quality of power met IEEE1547.4 guidelines. The IEEE1547.4 document describes many guidelines for meeting the load conditions for the microgrid and is dependent on fully understanding the existing load conditions that the microgrid will need to maintain. Ranges for meeting power quality standards are contained in ANSI/NEMA C84.1-2006 and referenced in IEEE1547.4. A summary of the important requirements listed in 1547.4 are shown in Table 6-1 along with the description of compliance based on data collected during islanding testing.

Table 6-1: Summarized IEEE1547.4 requirements pertinent to ESTCP demonstration

IEEE 1547.4 Paragraph No	Requirement Description	Compliance Description
4.2	The planned DR island system shall maintain voltage and frequency for the entire island system including the non-participating DR systems and loads.	Voltage and frequency were maintained to ANSI/NEMA C84.1-2006 ranges during the demonstration.
4.2	In a planned island loads shall be balanced for each phase. [Calculation for voltage balance is in C84.1 -2006 and should limit unbalance to 3%. Example: with phase-to-phase voltages of 230, 232, and 225, the average is 229; the maximum deviation from average is 4; and the percent unbalance is (100 X 4)/229 = 1. 75 percent.]	L1 Ave = 118 L2 Ave = 118 L3 Ave = 118 Max Deviation from Ave = 0 (100x0)/118 = 0 Data shown in Figure 6-2
5.1.2	The reactive power requirements of the DR island system during the island condition are important to consider. DR shall support real and reactive load requirements at an acceptable voltage level. The reactive power requirements of the load during island conditions needs to be understood in relation to the real power requirements of the load and the DR island reactive power resources.	Voltages were maintained within ANSI/NEMA C84.1-2006 ranges under reactive power conditions.
5.1.2	Reactive power resources shall be sufficient not only to address steady-state reactive power demands, but also to address dynamic reactive power demands, such as those related to motor starting within the DR island system. There are possible interactions between the customer's and area EPS's power factor correction equipment and synchronous motors and DR. There needs to be sufficient reactive power resources available when operating induction or some inverter-based DR.	The ESS provided sufficient reactive power to address dynamic reactive power demands. HVAC units were utilized to create reactive power loads.
5.1.4	DR island systems shall be capable of starting and maintaining motor operations. Motor-starting inrush current can exacerbate voltage drops in the DR island system. This voltage drop may result in a degraded ability to start the motor or cause loss of generation. Extended motor acceleration times may cause excess heating, which may reduce motor life and may cause motor overcurrent protective devices to operate. Soft- start controllers or reduced voltage starters on large motors can reduce inrush currents and thus minimize their impacts.	HVAC units within building 6311 were turned on repeatedly during testing to create motor-starting inrush currents. The ESS was able to meet these loads while maintaining voltage levels per ANSI/NEMA C84.1-2006.
4.4.3	The DR island system shall provide the real and reactive power requirements of the loads within the island and serve the range of load operating conditions. [TBR – Using Miramar 6311 Load Data]	Variable load conditions were created during islanding tests and they were all met.
4.4.3 & 6.1	The DR island system shall actively regulate voltage and frequency within the agreed upon ranges (e.g., as specified in ANSI/NEMA C84.1-2006 for DR island systems that include the area EPS). Voltage regulation equipment	L1 Vmax = 121.63 / L1 Vmin = 111/18 L2 Vmax = 121.42 / L2 Vmin = 110.64 L3 Vmax = 121.46 / L3 Vmin = 109.97

	within the DR island system may need to be modified to meet the needs of the DR island system. [TBR – 184Y/106V to 220Y/127V, 59.3 Hz to 60.5 Hz]	Shown in Figure 6-2 and Figure 6-1
4.4.3	During the island mode condition, transient stability shall be maintained for load steps, DR unit outage, and island faults.	Transient load steps were created with HVAC units kicking on repeatedly as well as PV generation sources turning off during islanding testes. The system maintained power quality throughout the demonstration.
4.4.3	If there are multiple DR units in the DR island system, their operation shall be managed and coordinated to effectively meet the needs of the island.	Both ESS and PV power were utilized in the islanding demonstration. The PV and ESS were coordinated by the IPEM controller adequately during the test.
4.4.4	Once the DR island system is paralleled to the area EPS, all DR shall return to IEEE 1547 compliance within area EPS time requirements. [TBR 1hr in the Demo Plan]	The goal for the project was to re-connect the system within 1hr and this was achieved during the testing.

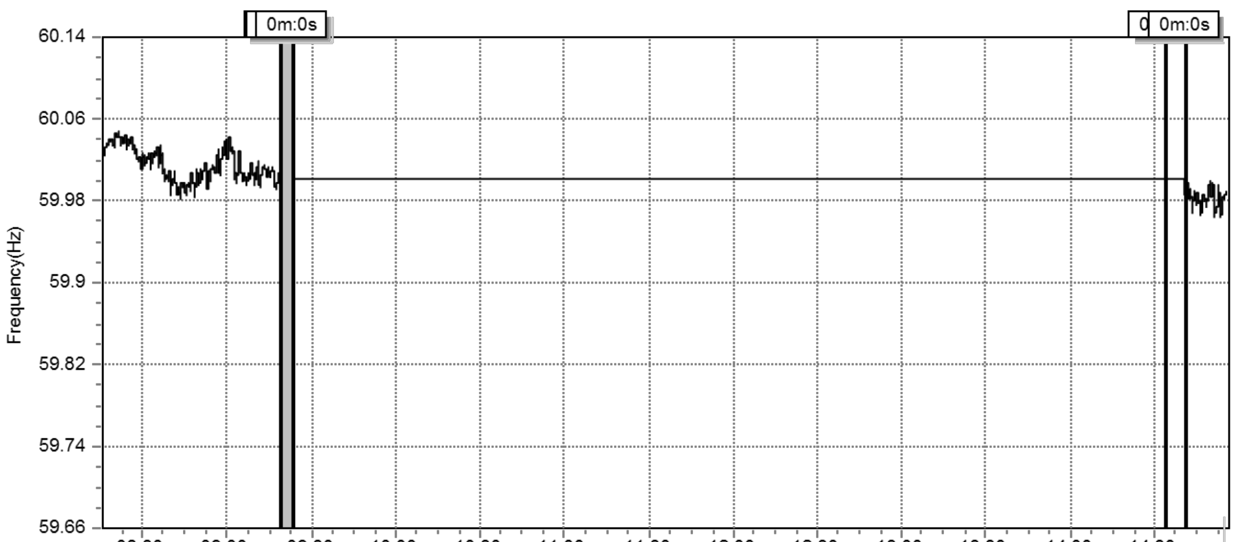


Figure 6-1: Frequency measurements during 12/13/15 islanding demonstration test. Data was taken from Fluke 437 power analyzer. Frequency was maintained at a very stable 60hz.

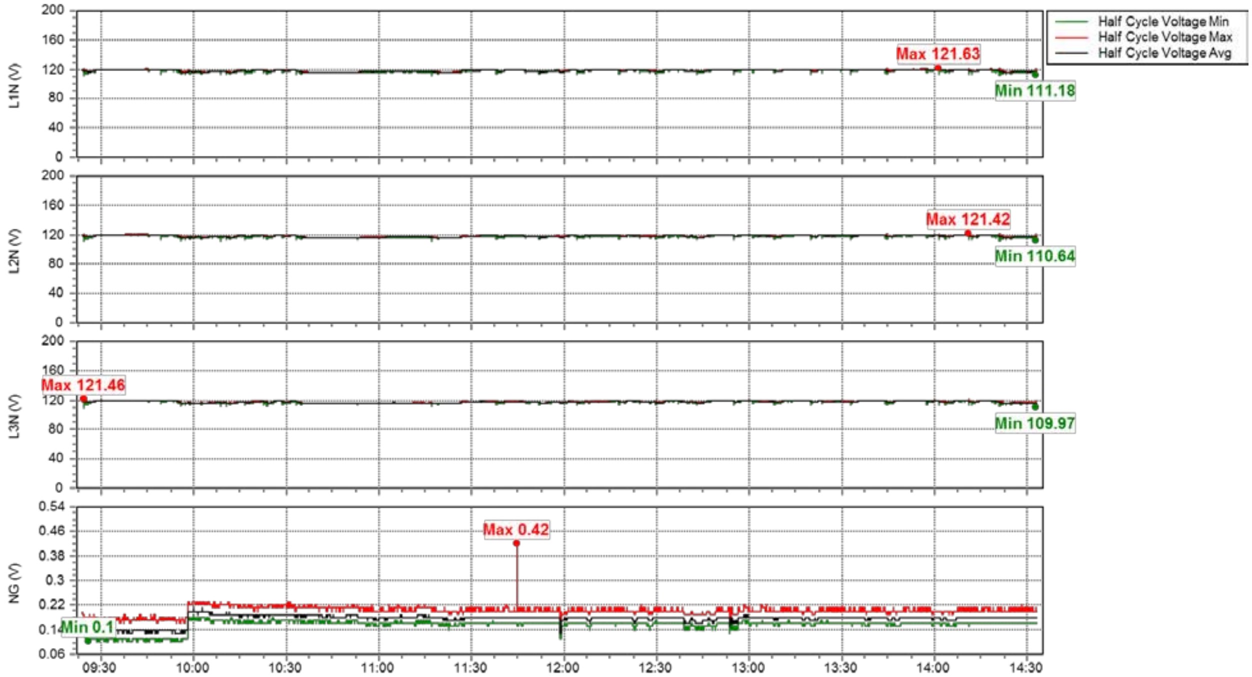


Figure 6-2: Phase to phase voltage data during 12/13/15 islanding demonstration test.

After post processing the data collection and further investigation it was determined that the reason the battery went into inactive mode was because there was a power supply failure in one of the control boxes of an EnergyCell. This resulted in the loss of gate power to one of the H-bridges which triggered a fast fault in the ESS causing the central regulator to ramp itself down and set the battery in inactive mode. Therefore it was concluded that there was still energy capacity still remaining in the battery when it went inactive. This is supported by voltage measurements collected on the DC string voltage in the ESS and the DC power injected into the Parker Inverter (Figure 6-3). The ESS discharged ~159kWh of energy during the demonstration. The ESS has been calculated to have ~290kWh of energy capacity based on the energy capacity tests. This would have left ~131kWh of energy remaining in the ESS. The average load from 6311 was ~64kW during the islanding demonstration therefore the Islanding demonstration should have been able to run for another 2 hrs at the average 64kW load. This would have put the islanding time at a theoretical 7 hours and 10 minutes for those load conditions.

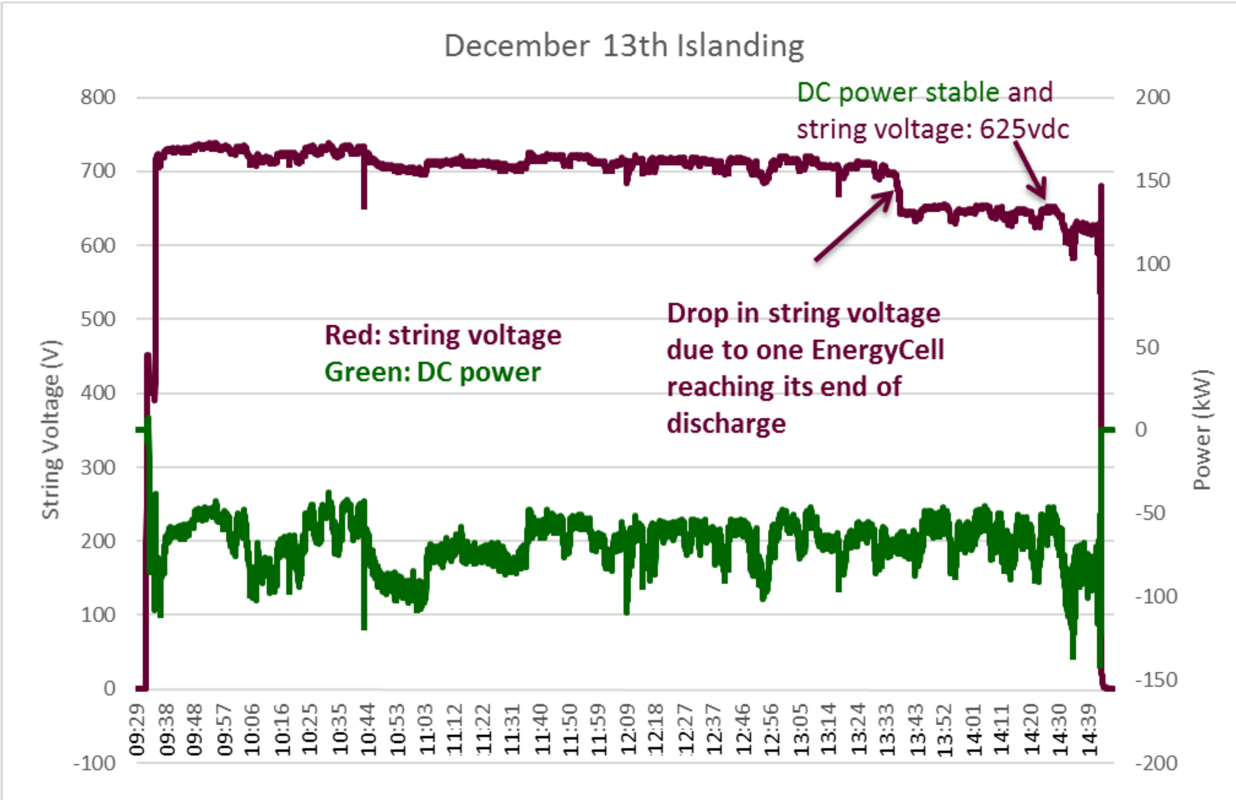


Figure 6-3: Voltage measurements on the EnergyCell string and DC output power from the Primus central regulator going into the Parker inverter. At ~1:40PM one of the twelve EnergyCells active during the test reached its end of discharge and took itself out of the string, dropping the string voltage. The string voltage appears stable all the way to point the fault occurred.

6.2 BUILDING LOAD REDUCTIONS

The success criteria for this objective is that building loads can be reduced by 50% through manual changing of thermostats and lighting when compared to its previous year's average for that given month. Building load reduction capability was calculated to be 68% from manual changing of thermostats and DDC control set points during the islanding testing. The data showing the increased manual load steps is shown in Figure 6-4 and represented in 100*(25-78)/78 = -68%.

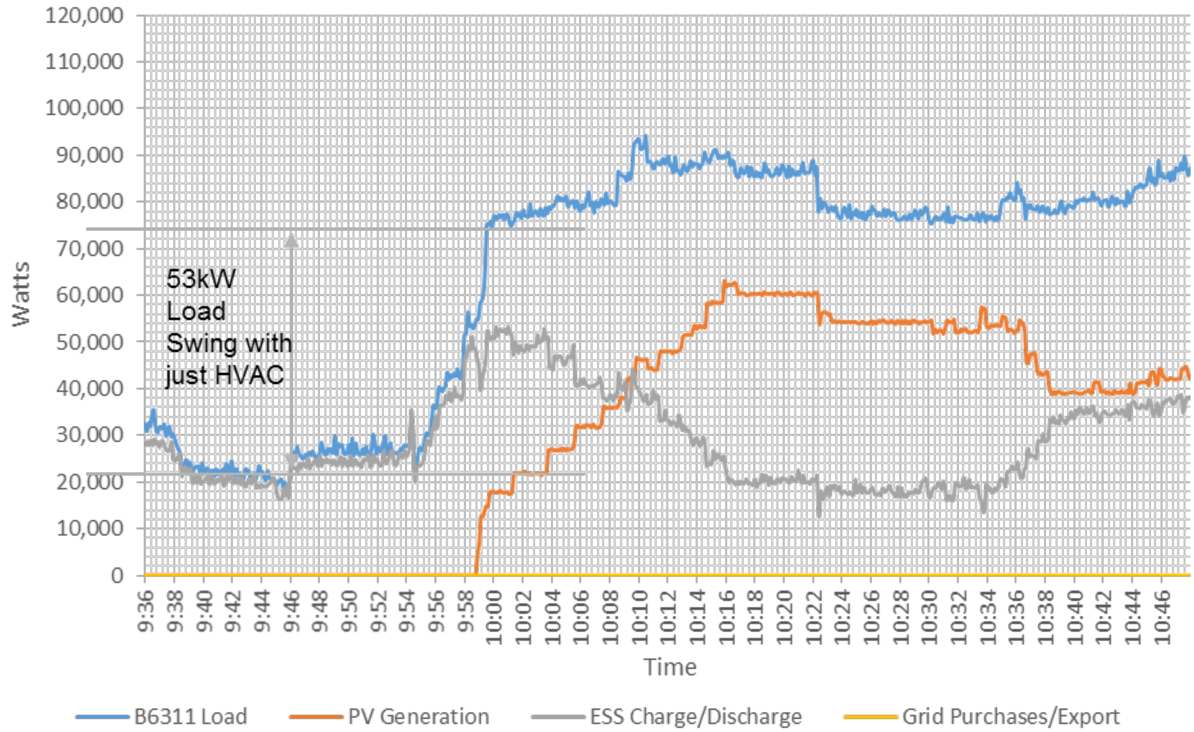


Figure 6-4: Load profile from 12/13/15 islanding demonstration test highlighting load steps from manually increasing HVAC and building loads.

6.3 SWITCHOVER TIME

Switchover time is the time from when the system is commanded to enter islanding mode to the time power is restored to building 6311 by the microgrid. The success criteria for this Performance Objective is defined to be is less than 1 hour. During the 12/13/15 islanding demonstration test the time it took the system to transition into islanding mode was recorded at 3 minutes and 47 seconds and is shown in Figure 6-5. When the islanding event was over and the system needed to restore grid power the time it took for the system to re-connect to the grid was also recorded and was 7 minutes and 1 second. The timeline for switching the system into islanding mode starts when the system is commanded via the IPEM HMI to enter islanding. The IPEM controller disables the PV inverters, sets the ESS in standby, checks the safety interlocks within the switchgear then opens the main breaker. The IPEM controller then commands the ESS to enter islanding mode. This reboots the Parker Inverter within the ESS in voltage control mode which takes under a minute. Once booted successfully the ESS starts to ramp up the voltage on the DC bus. This takes a couple minutes for each EnergyCell to be added to the DC bus. Once the DC bus is above 600V the Parker inverter closes its AC breaker and power is provided to the microgrid. For switching out of islanding the system is restored to grid power via the IPEM HMI. The IPEM controller then disables the ESS and PV inverters if the they are still running, if not it sets then in standby while they are in backup power mode. The IPEM controller then checks the status of the base Grid to see if it is active through the phase rotation relay. If the Grid is present and everything is in standby IPEM closes the main breaker restoring power to the building. This is shown in Figure 6-6.

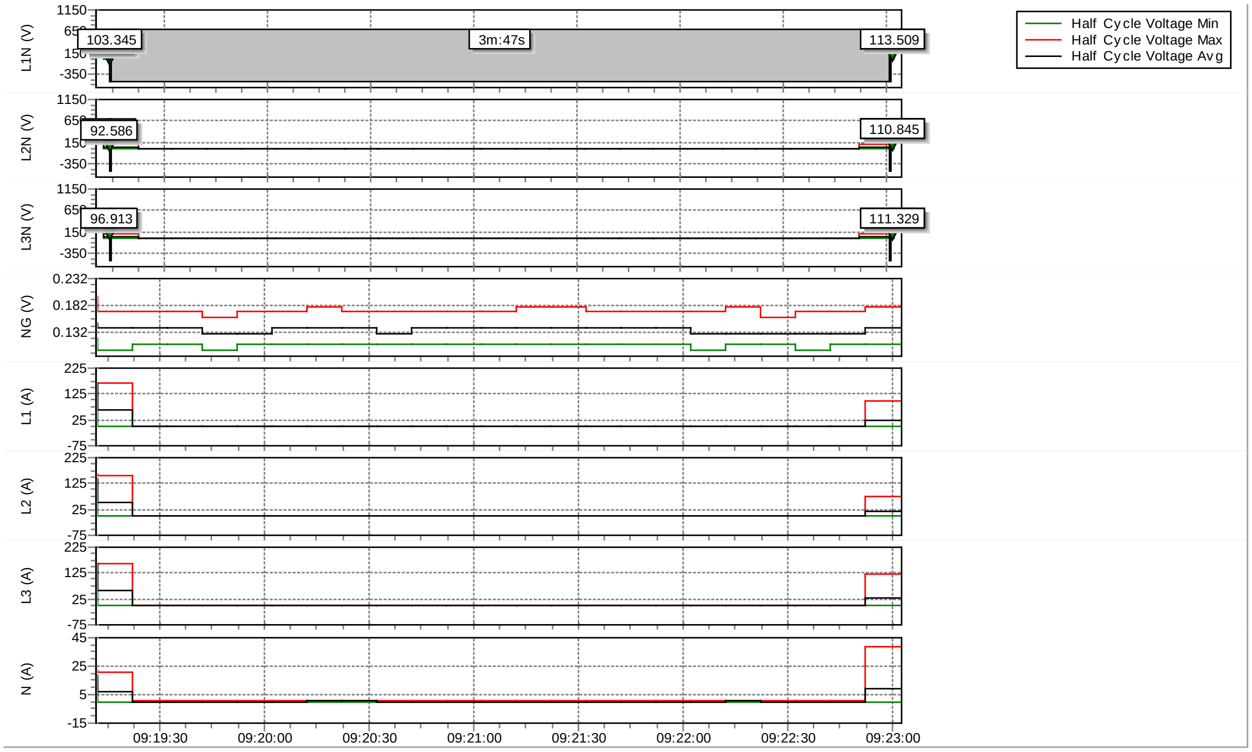


Figure 6-5: Outage time from 12/13/15 islanding demonstration test to enter islanding mode. Grey box in L1N shows time recorded by Fluke 437 showing when the voltage was dropped and then restored.

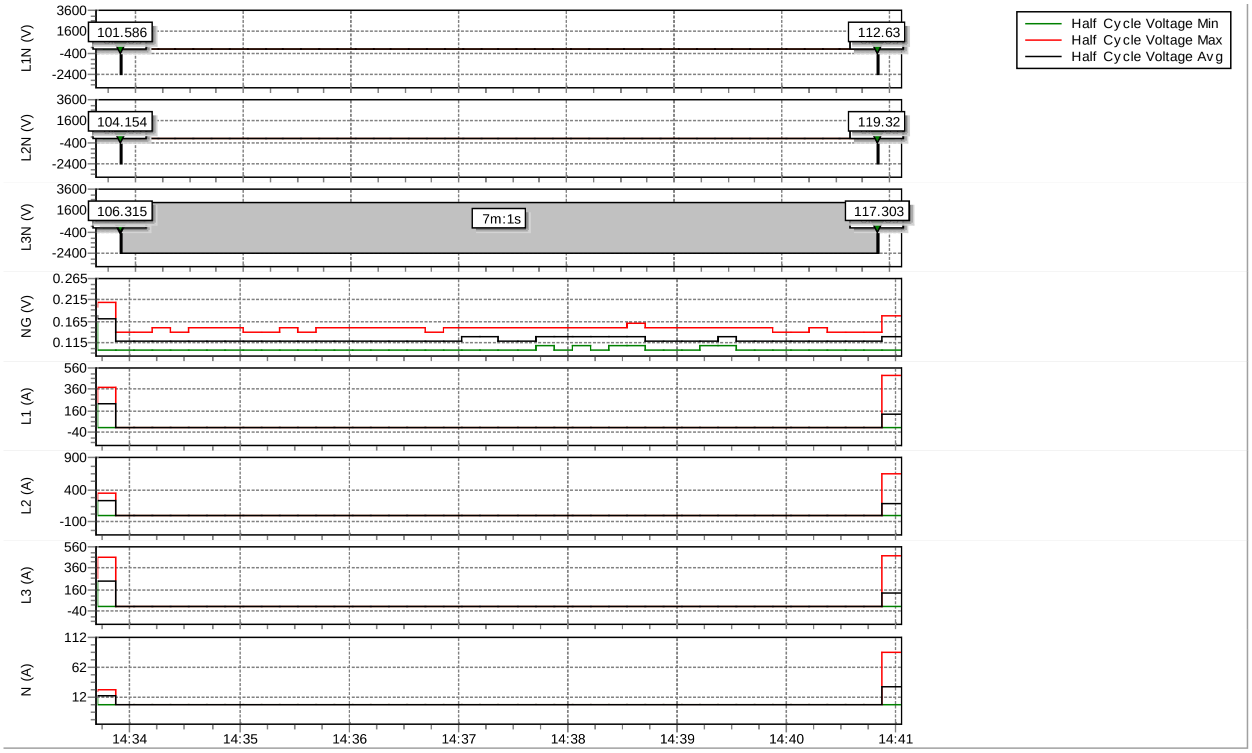


Figure 6-6: Outage time from 12/13/15 islanding demonstration test to exit islanding mode. Grey box in L3N shows time recorded by Fluke 437 showing when the voltage was dropped and then restored.

6.4 PEAK SHAVING

There are two pieces of data required to calculate the Peak Shaving metric. The first is relevant historical load profile data. This data was collected a couple days prior to using the ESS in peak shaving mode and is shown in Figure 6-7.

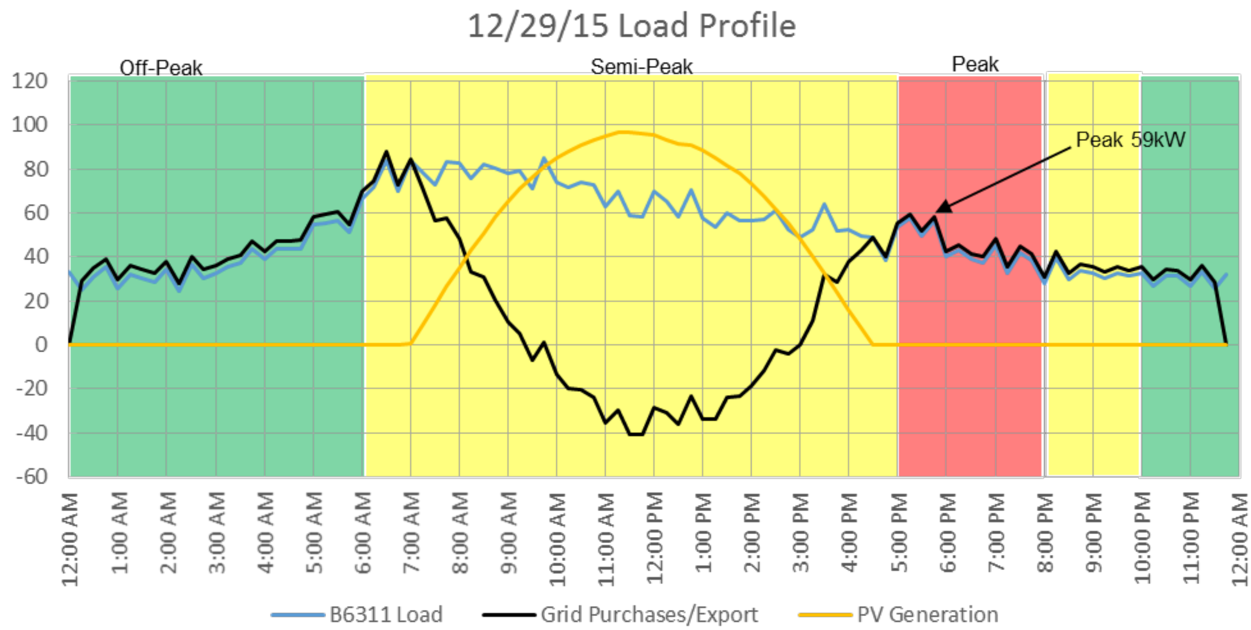


Figure 6-7: A graph showing a historical load profile of a building.

The second piece of data is the load profile when using the ESS in its peak shaving mode. The metering points for the load was collected at the B5PS2T3 switch gear according to the CT locations defined in Figure 2-10. The load data collected is summarized and shown in Figure 6-8 below.

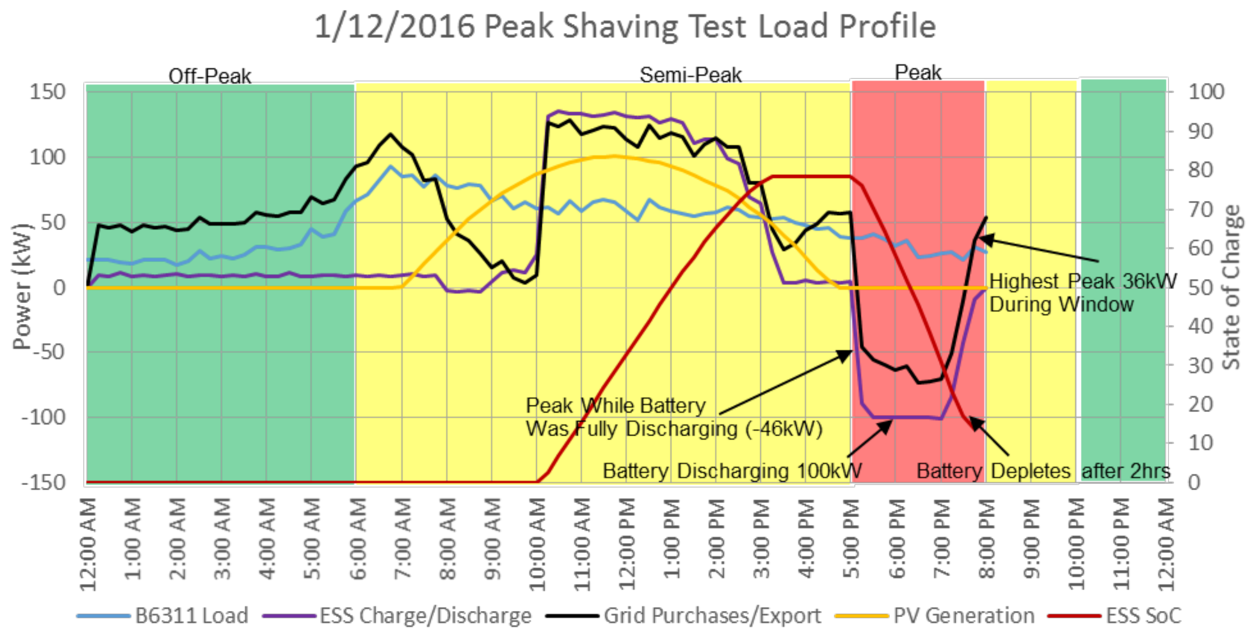


Figure 6-8: Peak shaving test data.

Both the historical load data and load data used in peak shaving mode are compared to each other to quantify the peak shaving difference achieved.

The success criteria for this metric was originally determined to be that the ESS is able to store energy during off peak time and discharge 250 kW during peak time to reduce peak load relative to historical data over similar time period.

Based on the energy capacity available in the ESS installed at MCAS Miramar and that the demonstration wanted to perform against SDG&Es winter TOU Peak time period it was determined that the ESS should be set to discharge at 100kW power output to achieve 3 hours of required discharge. During the test the battery started discharging at 5PM at 100kW and was able to drop change the profile of the Grid purchases at the main feeder metering point to export 46 kW of power into the distribution system as shown in Figure 6-7. At approximately 7PM, after two hours of discharging the battery started approaching 30% state of charge and the total output power of the battery started to diminish less than 100kW and slowly lessened until the battery was unable to provide power out any longer just before 8PM. The end result showed that the battery was capable of peak shaving at 100kW for just under the 3hrs but not long enough to get through the whole Peak time period of 3hrs. The ESS would need to be set to a lower power discharge output to get through the entire 3hrs.

The data was then compared to the base line data collected prior to conducting the peak shaving. Figure 6-9 below shows the comparison to the two load profiles. The two load profiles show similar load characteristics. The base load of the circuit operates between 30-50kW. As people get to work in the morning there is an uptick in load on the circuit as lights are turned on an people start their workday in the office. Sun rise this time of year is between 6:45AM-7AM and it is shown that the load starts dropping as the PV systems start to generate power. The real differences occur at 10AM when during the Peak Shaving test the ESS was set to charge which is why there is a sudden ramp in load. At ~3:25PM the charge was stopped and the ESS dwelled at until 4:50

where the ESS was set to discharge at 100kW output. From here the delta between the two load profiles is shown to be 105kW validating the 100kW capability of reducing demand during peak time. At 7PM the battery started to reduce its power output as it neared the lower end of its State of Charge causing the Grid load to rapidly increase until the battery was fully depleted at ~8PM. If this system was metered by SDG&E the peak demand measured would have been 36kW right before 8PM negating demand reduction achieved between 5PM-7PM. This shows that the output power of the battery would need to be reduced in order to discharge for the full 3hrs.

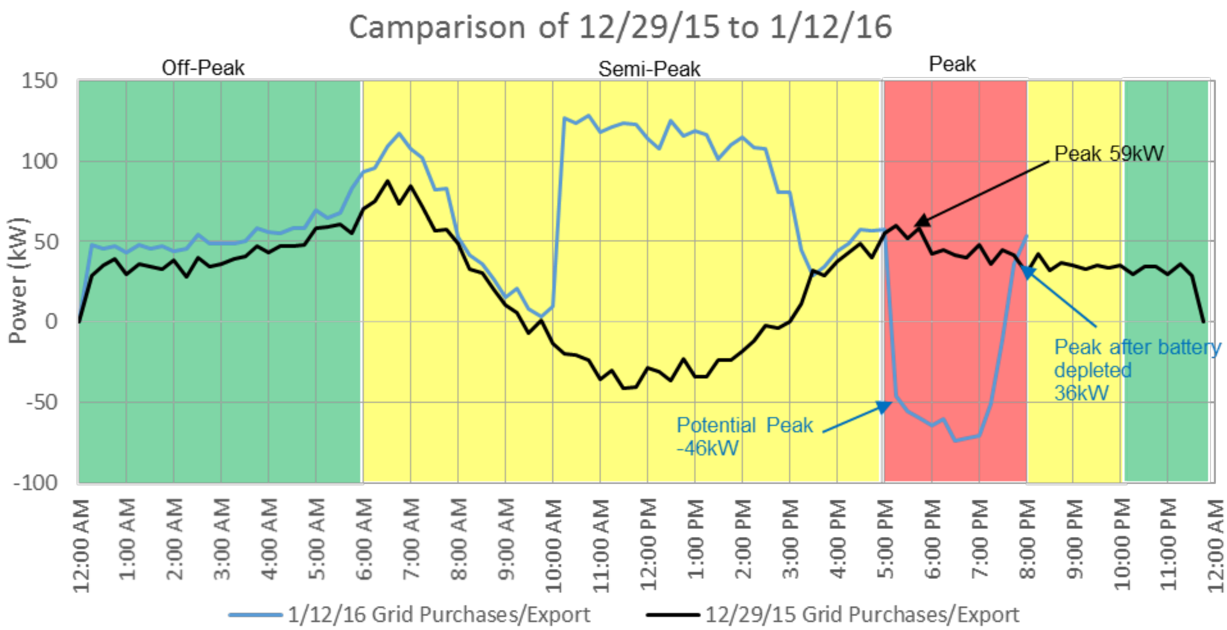


Figure 6-9: Comparison of the load data collected on 12/12/15 to the data collected during the peak shaving test on 1/12/16.

6.5 ESS ENERGY STORAGE CAPACITY

The data required for this Performance Objective is power output of the ESS and recorded time of the power output. This was captured on two different days of performing this test. The first day captured was on 11/15/2015 and the second was captured on 11/17/2015 and is shown in Figure 6-10 and Figure 6-11 below.

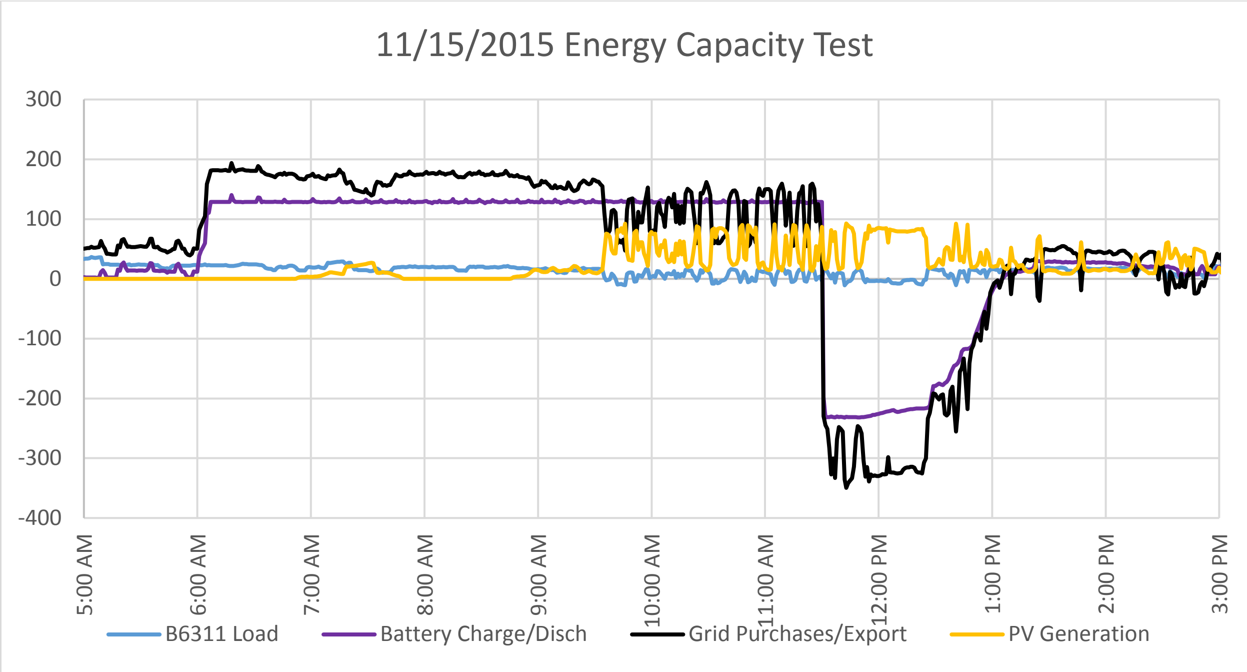


Figure 6-10: Energy Capacity test conducted on 11/15/15. The discharge output of the battery was set to 230 kW output power.

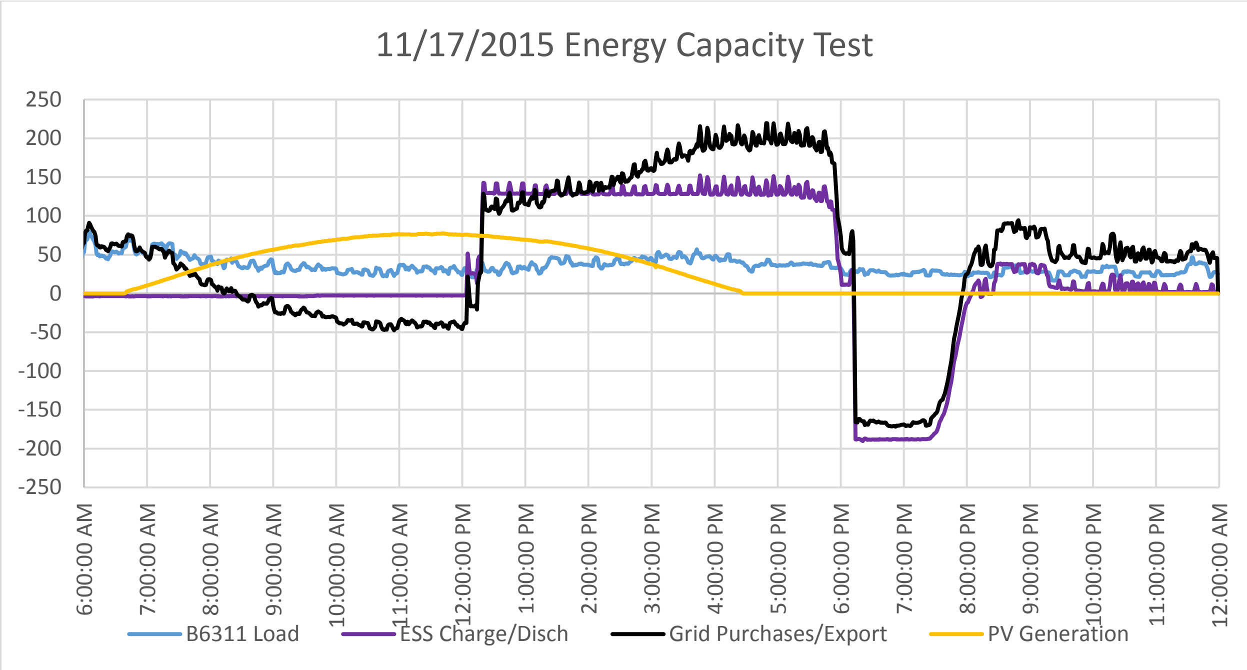


Figure 6-11: Energy capacity test conducted on 11/17/2015. The discharge output of the battery was set to 190kW output power.

The measurement of power over time was analyzed and the energy capacity of the system was calculated to be the integral of the graph from the beginning of discharge to the time that the power output of the battery reaches zero. The data collected on 11/15/15 and 11/17/15 was integrated

over the time that the battery was discharging to determine the total discharge energy from the ESS. The summary of the data is shown in Figure 6-12 and Figure 6-13 below. The ESS achieved 281kWh of energy capacity when discharged at 230kW power output and 294kWh when discharged at 190kW power output.

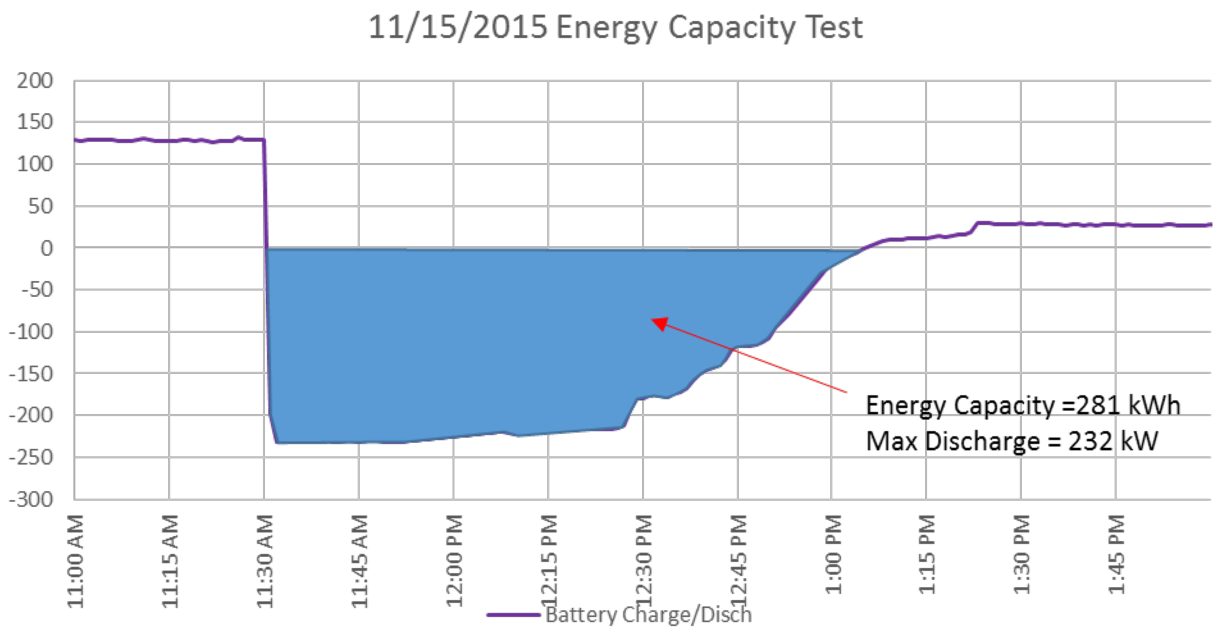


Figure 6-12: Energy capacity calculated for 11/15/15 test.

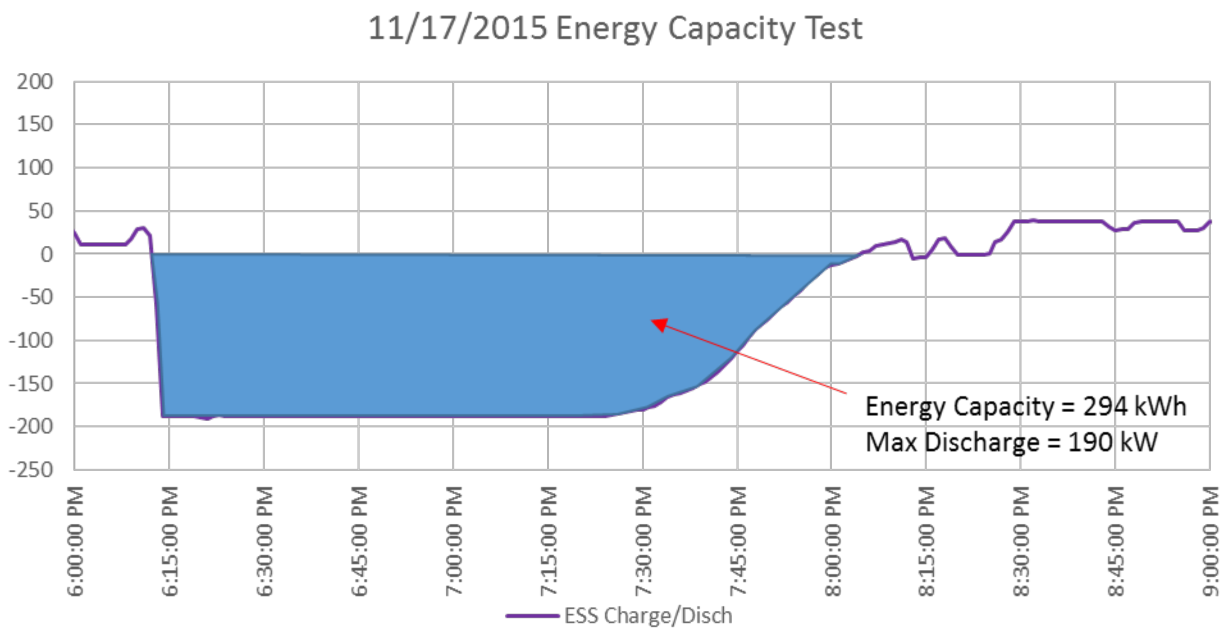


Figure 6-13: Energy capacity calculated for 11/17/15 test.

7 COST ASSESSMENT

This project is intended to demonstrate that an energy storage system can be used as a replacement for conventional diesel generators for emergency back-up power and show that an ESS can function within a microgrid during islanded operation to enhance energy security. This project also intends to show that an ESS can be used for economical benefits by changing the load profile of a building by charging and discharging the battery according to a controlled schedule.

7.1 COST MODEL

The cost model was updated from what was calculated in the Demonstration Plan. The Demonstration Plan that was submitted earlier in the project utilized the performance objectives for peak shaving and islanding time to calculate the theoretical savings if those objectives were realized. The cost model was updated based on the demonstrated performance of the installed system.

Putting a cost assessment to the energy security aspect of this project is very difficult. NREL has come up with using a Customer Damage Function (CDF) which tries to determine interruption costs as a function of outage duration (Giraldez 2012). The CDF function for Miramar was calculated to be $725/kW peak in a non-emergency situation for the islanding duration objective of 72hrs. Since the system was only able to achieve a maximum theoretical islanding duration of 7hrs that will be the number used to calculate the CDF. This puts the CDF at $120/kW peak for a non-emergency situation. Building 6311 had a maximum peak of 130kW in 2012. Therefore the CDF of building 6311 yields $15,600 of cost associated with an outage of 7hrs. According to SDG&E records over the last 10 years there are two spikes of outages recorded that impacted customers in 2003 and 2011; therefore it will be assumed that over a 20 year period of operation the ZnBr ESS installation will be used twice for back-up operations, and assumed to happen at year 1 and year 10.

Since the probability of an outage occurring is a rare occurrence, the peak shaving mode of the system is meant to provide economical benefit to the end user. This benefit will also be used to calculate the operational cost reductions when using the system in addition to abating the CDF associated with an outage.

The annual savings for operating in peak shaving mode were calculated using load data from MCAS Miramar and SDG&E's 2014 AL-TOU rate sheet for energy calculations (Figure 7-1). A model was used that controls the energy storage unit to charge during off peak times and discharge during peak times. SDG&E has different peak times for winter and summer operations so the

energy storage unit was controlled differently during the winter and summer.

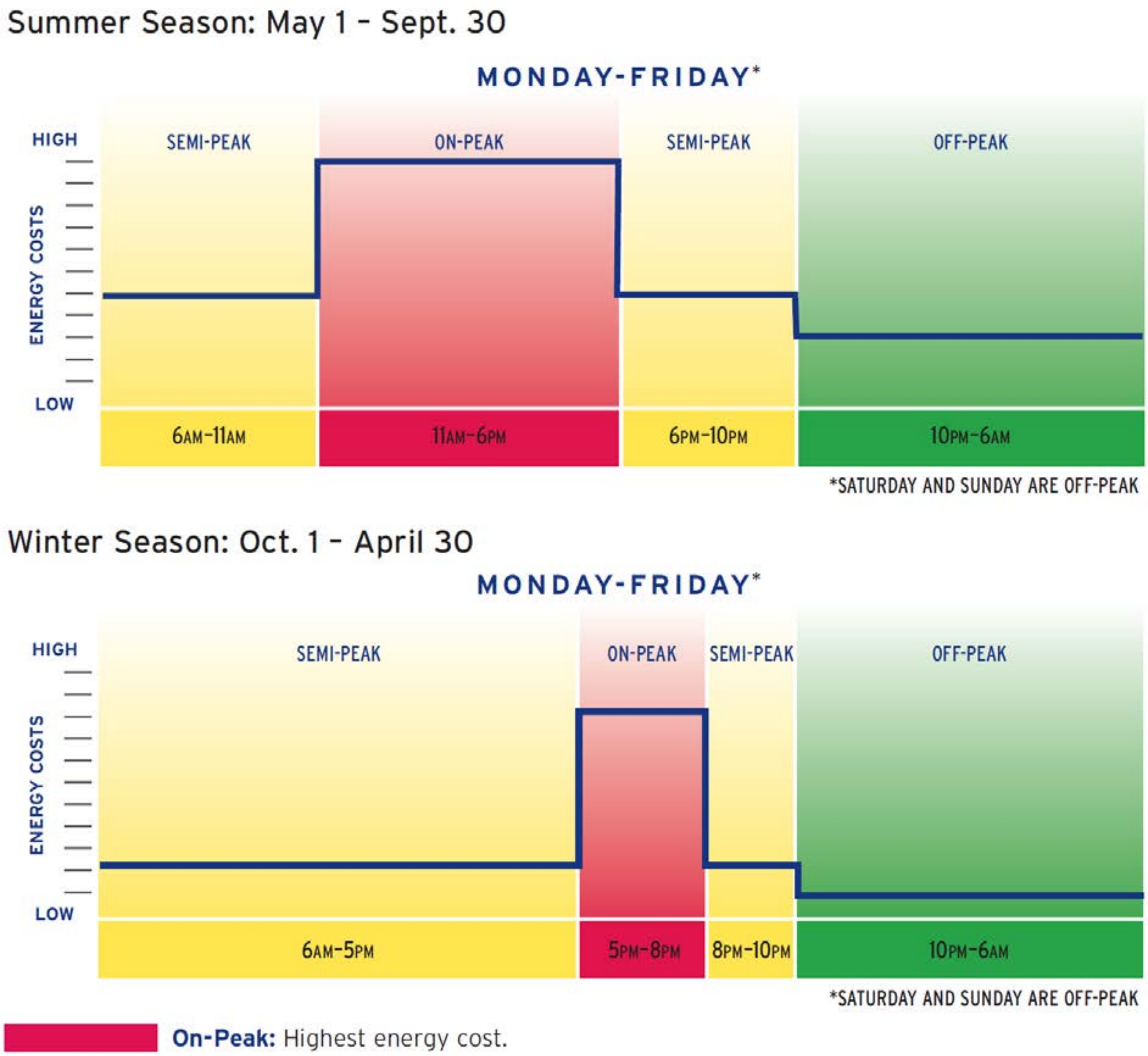


Figure 7-1: SDGE Time of use schedule graphic.

The ESS was commanded to charge during off-peak hours and discharge during peak hours. The model was run for a year's profile. For each billing month the non-coincidental peak, the on-peak peak, and the energy charges were calculated for the normal load curve and the grid purchases curve when using the ESS in peak shaving mode. The result of the model showed there was a \$37k savings in demand charges and energy charges when using the ESS in peak shaving mode.

The cost elements associated with this assessment are shown in Table 7-1 below.

Table 7-1: Cost Model for an Energy or Water Technology

Cost Element	Data Tracked During the Demonstration
Hardware capital costs	ESS \$840k, IPEM \$41k

Installation costs	Primus Power $37k, Dynalectric Construction $519k
Consumables	No consumables used.
Facility operational costs	$10k/yr operational cost savings when used in peak shaving mode
Maintenance	ESS requires annual maintenance at $30k/yr
Hardware lifetime	ESS cells are designed to last 20 years
Operator training	$30k for operator training
Salvage Value	Removal of equipment is $67k and the salvage value is $471k using Single Present Value calculation from NIST Handbook 135.
Customer Damage Function (CDF) Abatement	$15.6k two times over 20 years

Total Lifecycle Costs (TLC) for the system assumes a 20 year life and includes the following:

TLC = [Hardware capital costs] + [Installation costs] + [Operator training] + [UPV Maintenance Costs] - [UPV* Operational Cost Reductions] - [SPV Salvage Value] – [CDF Abatement]

<u>UPV Maintenance Costs</u>

UPV Maintenance Costs are calculated using NIST Handbook 135.

$$UPV\ Maintenance\ Costs = AxUPV_N$$

Where A = $30k

UPV_N = 14.88 taken from Table A-2 in NIST Handbook 135 Annual Supplement

UPV Maintenance Costs = $446k

<u>UPV* Operational Cost Reductions</u>

UPV* Operational Cost Reductions are calculated using NIST Handbook 135

$$UPV^*\ Operational\ Cost\ Reductions = AxUPV_N^*$$

Where A = $10k based on using SDG&E AL-TOU Primary rate sheet and peak shaving performance demonstrated for 40kW of peak shaving in the summer and 100kW of peak shaving in the winter.

UPV^*_N = 20 taken from Table A-3a in NIST Handbook 135 Annual Supplement using a 3% increase in price.

UPV* Operational Cost Reductions = $200k

<u>SPV Salvage Value</u>

SPV Salvage Value is calculated using NIST Handbook 135.

$$SPV\ Salvage\ Value = CxSPV_t$$

Where C = $840k

SPV$_t$ = 0.554 taken from Table A-1 in NIST Handbook 135 Annual Supplement

SPV Salvage Value = $465k

CDF Abatement

CDF abatement consists of two values, an abatement assumed at year 1 and an abatement assumed at year 10. The abatement at year one is $15.6k based on the CDF function described earlier. The abatement at year 10 is calculated using SPV in NIST Handbook 135 Annual Supplement.

$$CDF\ Abatement = A + A\ x\ SPV_t$$

Where A = $15.6k based on using SDG&E AL-TOU Primary rate sheet

SPV$_t$ = 0.744 taken from Table A-1 in NIST Handbook 135 Annual Supplement

CDF Abatement = $27.2k

Using the formulas above and date from Table 7-1 yields the following results for TLC.

TLC = [$881k] + [$556k] + [$30k] + [$446k] - [$200k] - [$465k] – [27.2k] = ~1,221k

The Total Lifecycle Cost for this system is $1,221k over a 20 year period and is shown in Table 7-2 for each year. The cost model indicates that with the current performance of the system the cost savings due to operating the system do not generate a full payback within 20 years. If the system achieved the original performance objectives the cost model is described in section 7.3.

Table 7-2: TLC cost for each year for a 20 year period.

Year	UPV* Operational Cost Reductions	SPV Salvage Value	UPV Maintenance Costs	CDF Abatement	TLC
1	($10,065)	($815,640)	$29,100	($15,600)	$654,795
2	($20,130)	($792,120)	$57,300		$696,450
3	($30,195)	($768,600)	$84,900		$737,505
4	($40,260)	($745,920)	$111,600		$776,820
5	($50,325)	($724,920)	$137,400		$813,555
6	($60,390)	($703,080)	$162,600		$850,530
7	($70,455)	($682,920)	$186,900		$884,925
8	($80,520)	($662,760)	$210,600		$918,720
9	($90,585)	($643,440)	$233,700		$951,075
10	($100,650)	($624,960)	$255,900	($11,606)	$970,084

11	($110,715)	($606,480)	$277,500		$1,000,099
12	($120,780)	($588,840)	$298,500		$1,028,674
13	($130,845)	($572,040)	$318,900		$1,055,809
14	($140,910)	($555,240)	$339,000		$1,082,644
15	($150,975)	($539,280)	$358,200		$1,107,739
16	($161,040)	($523,320)	$376,800		$1,132,234
17	($171,105)	($508,200)	$395,100		$1,155,589
18	($181,170)	($493,080)	$412,500		$1,178,044
19	($191,235)	($478,800)	$429,600		$1,199,359
20	($201,300)	($465,360)	$446,400		$1,219,534

7.2 COST DRIVERS

For this particular project since the energy storage technology was scaling up its system for the first time there were cost drivers associated with building the first large prototype. Developing a scalable low cost manufacturing process takes time and investment. Primus Power was able to balance the uncertain costs of building a first of a kind unit with the unknown costs that are normally associated with developmental technologies. Because of anticipated delays in manufacturing and increased costs associated with developing their manufacturing line Primus had to deliver a system that was fully functional and tested however was at reduced performance levels due to the high costs of their Gen 1 prototype. Going through the experience of building their first full scale system has allowed Primus to understand the behavior and performance of their system at scale. This has been taken and applied to a Gen 2 version that is capable of meeting the performance objectives of the original system at the anticipated original costs.

Other cost drivers for this type of technology implementations are the siting and infrastructure upgrades required to accommodate new generation assets on an older distribution system. One of the large costs on the installation of this project was the upgrades to the switchgear and the transformer as well as creating a concrete pad for the ESS to sit properly.

7.3 COST ANALYSIS AND COMPARISON TO FULLY FUNCTIONAL SYSTEM

This section describes the cost analysis for a fully functional system that is capable of meeting the performance goals (like implementing the Gen 2 of Primus' system).

The cost elements associated with this assessment are shown in Table 7-3 below.

Table 7-3: Cost Model for an Energy or Water Technology

Cost Element	Data Tracked During the Demonstration
Hardware capital costs	ESS $840k, IPEM $41k

Installation costs	Primus Power $37k, Dynalectric Construction $519k
Consumables	No consumables used.
Facility operational costs	$37k/yr operational cost savings when used in peak shaving mode
Maintenance	ESS requires annual maintenance at $30k/yr
Hardware lifetime	ESS cells are designed to last 20 years
Operator training	$30k for operator training
Salvage Value	Removal of equipment is $67k and the salvage value is $471k using Single Present Value calculation from NIST Handbook 135.
Customer Damage Function (CDF) Abatement	$94k two times over 20 years

Total Lifecycle Costs (TLC) for the system assumes a 20 year life and includes the following:

TLC = [Hardware capital costs] + [Installation costs] + [Operator training] + [UPV Maintenance Costs] - [UPV* Operational Cost Reductions] - [SPV Salvage Value] – [CDF Abatement]

UPV Maintenance Costs

UPV Maintenance Costs are calculated using NIST Handbook 135.

$$UPV\ Maintenance\ Costs = AxUPV_N$$

Where A = $30k

UPV_N = 14.88 taken from Table A-2 in NIST Handbook 135 Annual Supplement

UPV Maintenance Costs = $446k

UPV* Operational Cost Reductions

UPV* Operational Cost Reductions are calculated using NIST Handbook 135

$$UPV^*\ Operational\ Cost\ Reductions = AxUPV_N^*$$

Where A = $37k based on using SDG&E AL-TOU Primary rate sheet

UPV^*_N = 20 taken from Table A-3a in NIST Handbook 135 Annual Supplement using a 3% increase in price.

UPV* Operational Cost Reductions = $740k

SPV Salvage Value

SPV Salvage Value is calculated using NIST Handbook 135.

$$SPV\ Salvage\ Value = CxSPV_t$$

Where C = $840k

SPV_t = 0.554 taken from Table A-1 in NIST Handbook 135 Annual Supplement

SPV Salvage Value = $465k

<u>CDF Abatement</u>

CDF abatement consists of two values, an abatement assumed at year 1 and an abatement assumed at year 10. The abatement at year one is $94. The abatement at year 10 is calculated using SPV in NIST Handbook 135 Annual Supplement.

$$CDF\ Abatement = A + A\ x\ SPV_t$$

Where A = $94k based on using SDG&E AL-TOU Primary rate sheet

SPV_t = 10 taken from Table A-1 in NIST Handbook 135 Annual Supplement using a 3% increase in price.

CDF Abatement = $164k

Using the formulas above and date from Table 7-1 yields the following results for TLC.

TLC = [$881k] + [$556k] + [$30k] + [$446k] - [$740k] - [$465k] – [164k] = $544k

The Total Lifecycle Cost for this system is $544k over a 20 year period and is shown in Table 7-2 for each year.

Table 7-4: TLC cost for each year for a 20 year period.

Year	UPV* Operational Cost Reductions	SPV Salvage Value	UPV Maintenance Costs	CDF Abatement	TLC
1	($37,000)	($815,640)	$29,100	($94,000)	$549,460
2	($74,000)	($792,120)	$57,300		$564,180
3	($111,000)	($768,600)	$84,900		$578,300
4	($148,000)	($745,920)	$111,600		$590,680
5	($185,000)	($724,920)	$137,400		$600,480
6	($222,000)	($703,080)	$162,600		$610,520
7	($259,000)	($682,920)	$186,900		$617,980
8	($296,000)	($662,760)	$210,600		$624,840
9	($333,000)	($643,440)	$233,700		$630,260
10	($370,000)	($624,960)	$255,900	($69,936)	$564,004
11	($407,000)	($606,480)	$277,500		$567,084

12	($444,000)	($588,840)	$298,500		$568,724
13	($481,000)	($572,040)	$318,900		$568,924
14	($518,000)	($555,240)	$339,000		$568,824
15	($555,000)	($539,280)	$358,200		$566,984
16	($592,000)	($523,320)	$376,800		$564,544
17	($629,000)	($508,200)	$395,100		$560,964
18	($666,000)	($493,080)	$412,500		$556,484
19	($703,000)	($478,800)	$429,600		$550,864
20	($740,000)	($465,360)	$446,400		$544,104

8 IMPLEMENTATION ISSUES

This program spans from inception back in 2011 all the way to the end of 2015. There were multiple challenges in implementing this program however each one was meant to implement final demonstration in December of 2015. A few standout implementation issues will be noted in this sections.

New Technology Development

Some of the challenges of achieving the desired islanding duration can be attributed to working with technologies that are in their final development phases. As part of the experience with working in the energy storage space it is shown that it is very difficult to scale systems up to utility scale. Fielding technologies that have been demonstrated in relevant lab environments is always a challenge and require iterations and lessons learned to optimize designs. This was realized early in this project when the original energy storage company that was proposed was not able to build the required unit due to challenges that arose in scaled units that were initially fielded. This prompted a change in ESS supplier after the program was under contract. Once a new supplier was selected the team had to manage a supplier that had promising technology however there systems were lower on the TRL scale than the previous supplier and the team had to manage technology that was in development and scale up simultaneously. This challenged the team in the decision making process as the team was continuously balancing performance and cost of the project appropriately to meet the demonstration objectives. This was shown near the end of the project where energy capacity performance of the ESS was demonstrated be near our objectives after our deployable system was ready but was not able to be implemented in our final demonstration unit.

Interconnect Agreement

Due to the fact that this program spanned multiple years, the process of obtaining the interconnect agreement from SDG&E took some understanding and effort. The use of large scale energy storage systems in microgrid capacities is new to the utility industry for behind the meter applications. Thus the interconnect agreement process is changing real time for utilities to adapt to how these systems will be deployed. This project was subject to some of the real time changes as a few iterations of the application were required due to changing application requirements. Ultimately the IA and permit to operate was granted due to hard work amongst multiple parties however it is still unclear if there is a well-defined process for getting IAs in place for microgrids.

9 References

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APPENDICES

APPENDIX A: POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
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Bob Riel	Dynalectric	858.712.4746 briel@dyna-sd.com	Project Manager
Bob Butt	NREL	303.384.7455 Robert.Butt@nrel.com	Project Manager